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STUDY OF CLIMATIC EFFECTS ON FAST ICE EXTENT AND ITS SEASONAL DECAY ALONG THE BEAUFORT-CHUKCHI COASTS

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1. SUMMARY .

The most significant hazard to offshore petroleum development along the Beaufort-Chukchi Sea coasts of Alaska is posed by the occurrence of sea ice for at least nine months of the year. As a basis for assessment of this hazard, the project had the following objectives: (1) to delimit the extent of fast ice along the Beaufort and Chukchi coasts prior to and during the decay season; (2) to define and characterize the nature of the summer decay of fast-ice from remote sensing data; (3) to determine climatic processes and meteorological synoptic events contributing to the spatial and temporal characteristics of fast-ice breakup and to examine their amenability to predictive assessment.

Ice conditions were mapped for 1973-76, primarily from Landsat satellite imagery; climatic conditions were studied for the available period of continuous records (since 1921 at Barrow).

Major findings are as follows:

(1) The rate and pattern of summer breakup of the fast ice in the Beaufort Sea is strongly influenced by the history of ice events during the preceding winter, and especially by the occurrence of grounded ridges between about 15 m and 30 m water depth. Along the Chukchi Sea coast a recurrent flaw lead south of Barrow facilitates ice movement once melt and cracking begins.

(2) The stages of fast ice decay and northward pack ice retreat on the Beaufort Sea coast can be correlated with the accumulated thawing-degree days (TDDs) .

(3) In order of importance, air temperature, sea-level pressure distribution, and surface wind direction account for most of the year-to-year variance in northward pack ice retreat in the Beaufort Sea; their correlation with ice retreat increases as the summer progresses.

(4) Light-ice summers in the Beaufort Sea are associated with southerly surface winds and a tendency for higher than normal pressure over the Arctic Basin centered about 80°N, 120°W, and lower than normal pressure over the East Siberian Sea, centered on 75°N, 170°E. The reverse is true for heavy-ice summers.

(5) The trends in sea-level pressure at 80°N, 120°W and 75°N, 170°E since 1939 and summertime TDDs since 1921 at Barrow indicate a decline in favorable mean ice conditions. Since 1953, 13 of 24 summers have accumulated over 400 TDDs (required for a northward retreat of the pack ice) while 28 of 32 summers from 1921 to 1952 did so. Heavy-ice conditions, such as those during 1955, 1975, and other recent summers, may not have occurred since before the mid-1920's.

(6) Monthly temperatures at Barrow in summer show some persistence that may be applied to forecasting breakup conditions. Summers with a predominance of monthly mean temperatures below normal, even with some normal months, will become severe ice years. Temperature persistence increases in late summer-autumn, implying applicability also to the timing of freeze up.

11. INTRODUCTION

A. General Nature of the Study

Nearshore ice along Alaska's Beaufort Sea and Chukchi Sea coasts undergoes an annual cycle of formation, extension, modification, ablation, and breakup. Many of the processes which contribute to this cycle are poorly understood, although it is generally recognized that meteorological and climatological factors are important influences for ice formation, motion, deformation, ablation, and breakup. This study has attempted to interpret ice characteristics and their time variations from remote sensing data supplemented by aircraft and field observations. This derived information covering both the Beaufort and Chukchi coasts has been compared with concurrent coastal weather conditions and regional atmospheric circulation patterns. On this basis, a systematic set of weather-ice relationships has been derived which, apart from their description of some anomalous conditions, can also provide a framework for predictive schemes.

B. Specific Objectives

(1) Map ice characteristics and behavior during the decay season of 1973-76 from available remote sensing data.

(2). Investigate surface weather data from the coastal stations and synoptic-scale atmospheric pressure patterns over the region to determine relationships between important ice-related weather "events" and the atmospheric circulation.

(.3) Examine the possibilities for predictive assessments of climatic factors influencing fast-ice decay and pack ice retreat.

C. Relevance to Problems of Petroleum Development

Offshore petroleum development may involve temporary operations on the winter fast-ice surface or in the open waters during summer. Alternately, large, ice-resistent structures may be used year-round. An accurate assessment of the best operational modes and of the seasonal distribution of ice hazards requires that the normal patterns of fast-ice characteristics and breakup processes and their interannual variability be specified. Also, the pathways of pollutants deriving from oil spills or blowouts are dependent to some degree on the season, and, in summer, on the relative progression of the breakup. It also seems significant that various faunal populations utilize the coastal environment, above and below the ice and in the open water areas. Seasonal and interannual variations in the weather and ice characteristics are important factors affecting the distribution and movements of these populations. These questions are elaborated in the report of the Beaufort/Chukchi Synthesis Meeting (Arctic Project Office, 1978).

The timing of major phases of the seasonal ice regime in the near-shore zone (i.e. melt in situ, first openings and movement, clearance along coast, etc.) and their interannual variability are of primary and most direct importance to offshore operations. The results summarized below address these questions. Also, the basis for a long-range ice forecasting technique has been developed, using air temperature at Barrow. This technique can be used to determine (i) when shipping can be expected to begin; (ii) the approximate length of the shipping season; (iii) the relative severity of summertime ice conditions.

111. CURRENT STATE OF KNOWLEDGE

The general characteristics of fast ice have been known for some time (e.g. Zubov, 1943), while more recent review of conditions in the Beaufort Sea fast-ice zone are given by Kovacs and Mellor (1974) and Reimnitz et al. (1976). The regional-scale dynamics of the fast-ice zone could not be effectively studied in detail until the launch of Landsat (formerly ERTS) in 1972. A good deal of literature has emerged since that time treating the information content of Landsat imagery of sea ice, but the OCSEAP Project represents the first systematic applied study of the regional scale surface morphology, composition and dynamics of fast-ice along the Beaufort and Chukchi Sea coasts. Our analysis complements the ice mapping studies of Stringer (OCSEAP Research Unit #258) .

Weather and climate have been studied by a number of authors (see e.g., Watson, 1968; Selkregg, 1974; Holmgren and Weller, 1974) for the Alaska region, and the Arctic atmospheric circulation has likewise been treated (e.g. Keegan, 1958; Reed and Kunkel, 1960; Wilson, 1967, Hare, 1968; Weller and Bowling, 1974). However, the relationships between ice decay processes and weather variations has hitherto received little attention, especially on the detailed scale required for BLM planning.

IV. STUDY AREA

The fast ice zone along the Beaufort and Chukchi Sea coasts between Demarcation Point and the Bering Strait represents the study area for this project. The seaward extent is variable according to season and location, but is generally about 50 km from the coast.

V. DATA

A. Remote Sensing

Regional scale mapping of the ice characteristics and behavior for 1973-76 has been carried out from Landsat imagery. Details of frames interpreted are given in the Quarterly Reports. Interpretation of categories of age, deformation, puddling of the ice, etc., has been performed with the aid of other remote sensing products (particularly aircraft SLAR and CIR) as well as reconnaissance observations and hand-held photography of the ice from aircraft.

B. Meteorological Data

The sources of data for the studies included here are as follows:

(1) National Weather Service station meteorological data for Kotzebue (1953-76), Barrow (1953-75) and Barter Island (1958-75) respectively. These data are published as Local Climatological Data. Parameters used are temperature (sometimes converted into thawing degree days), wind speed and direction, barometric pressure, cloud cover. Synoptic weather data for DEW-line stations (Deadhorse, Lonely, Oliktok) are also used for case studies.

(2) Daily (1200 GMT) grid-point data on MSL pressure for 1946-74 analyzed by NMC, NOAA (provided by NCAR, Boulder). These are used in the pressure pattern classifications and for computing geostrophic winds.

(3) Sea-level pressure maps for the Beaufort Sea prepared by AIDJEX for summer 1975.

C. Climate-Ice Interaction Case Studies

These studies utilised the above data sources and also tabulations of the retreat of fast-ice and pack ice off Barrow on September 15 of each year since 1953 (Barnett, 1976). Each summer is ranked according to its ice severity.

The analytical methods used in the case studies involved the characterization of particular ice events identified on Landsat imagery in terms of preceding and concurrent meteorological conditions. indices employed in the analysis include cumulative thawing degree days (sums of positive departures of daily average temperature above O*C).

The research strategy focussed on identifying links between climatological parameters, synoptic patterns of atmospheric circulation and processes of ice decay in the near-shore zone. This has also necessitated the determination of the initial state of ice conditions in spring. Mapping of winter ice events would necessitate repetitive SLAR imagery and supporting ground-truth information which were not available.

VI. RESULTS

A. Remote Sensing Interpretation and Ice Mapping

1. Ice Maps

The mapping of shorefast ice extent and morphological characteristics, as inferred primarily from available cloud-free Landsat imagery, has been carried out for the entire Beaufort Sea and Chukchi Sea coasts for the spring-summer seasons of 1973 through 1976.

For convenient references, a summary is given of the Annual Reports (AR) and Quarterly Reports (QR) containing these ice maps:

	1973	1974	1975	1976
A. Beaufort Sea:				
Barrow Sector	QR Sep.77	AR Mar.77	QR Sep.77	QR Dec.77
Prudhoe Sector	AR Mar.77	AR Sep.76	QR Sep.77	AR Mar.78
Barter Is. Sector	QR Sep.77	QR Sep.77	QR Sep.77	AR Mar.78
B. Chukchi Sea:				
Barrow Sector	AR Mar.77	AR Mar.77	AR Mar.77	QR Sep.77
Pt. Hope Sector	AR Mar.77	AR Mar.77	AR Mar.77	QR Sep.77
Kotzebue Sector	QRDec. 76	AR Mar.77	AR Mar.77	QR Sep.77

Summary maps showing the fast ice extent in early summer 1973-76 along both coasts are reproduced in Appendix 1.

The study necessitated the development of interpretive keys of ice conditions based on the remote sensing data. These included Landsat, some limited SLAR (side looking radar) imagery and high-level aircraft infrared photography. In addition, project personnel carried out low-level aircraft reconnaissance along the Beaufort coast in early summer 1975, 1976, 1977, and along the Chukchi coast in 1976 and 1977. Correlative analysis of Landsat images, SLAR imagery, and CIR photography, supplemented by field observations, shows that the following ice features can be located and identified:

(1) Large fields of level, hummocked, and ridged ice.

(2) Differentiation of first-year and older age categories, if the older ice inclusions are vast-floe (2-10 km) size or greater.

(3) Ice puddling characteristics: the integrated effects of puddle depths and percent areal coverage.

(4) Large, well-grounded ice features in the fast-ice.

(5) Ice concentration vs. open water.

(6) Time changes in the ice (motions, puddling increases, drainage, breakup).

A test of the spectral information content of Landsat data using the LARSYS system at Purdue University (through a subcontract with Laboratory for the Application of Remote Sensing, Purdue University) shows that during the melt season these data are mainly useful in determining the coverage and relative depth of surface melt pools on the ice.

A major problem with the Landsat data is the infrequent coverage and the high probability of cloud cover in the study area.

The average dates of significant ice decay events based on the Landsat analysis are summarized in Table 1. It should be stressed that these phenomena are large-scale (≥ 10 km^2) because of the satellite resolution. Motions can occur on various scales in the "fast" ice during winter, for example, but these motions are too small for Landsat to resolve. These dates can be viewed as climatological averages, with a probable variability (between years) of $\pm$ 10 days. The $\geq$14-day data gaps caused by the Landsat orbit do not permit better time resolution.

An overview of ice breakup processes along both coasts is given in Appendix 1. Some additional details for the Beaufort Coast are, however, appropriate here. The spring flooding of estuarine ice areas is most prominent along a short section of the coast including the Colville, Kuparuk and Sagavanirktok rivers. Other rivers showing some evidence of this phenomenon include the Canning, Sadlerochit, Hulahula, Jago and Aichikik rivers. Around mid-to-late June, the areas previously flooded by these rivers begin to develop shore-polynyi which spread laterally and seaward through mid-July. The largest of these (Colville) appears to allow an avenue of motion for shoreward-moving ice when breakup starts. Although the Meade, Chipp and Alaktok rivers do not exhibit large-scale flooding over the ice in May, they appear to enhance the ice melt in Dease Inlet and Smith Bay through the creation of shore polynyi in late June. Polynyi off Point Hope are discussed in Section VI C.

Surface meltwater on the ice shows considerable variations, both spatially in a given year and interannually at a given site. First-year "ice with relatively light deformation appears to pond the most melt-water. These areas often drain in late June or early July. Nevertheless, they are usually the first areas to melt through completely and break up. When older ice floes are incorporated into the fast-ice, they tend to persist late into the melt season. After the interstitial matrix of first-year ice has melted, however, these floes become mobile.

Large, grounded ice masses can be found in the fast-ice in any given year. Depending on the depth at which they become grounded, they may or may not represent the seaward edge of fast ice. It is certain, however, that well-grounded ice masses do not form a continuous, shore-parallel strip along the coast, but are separated by ice which is either poorly-grounded or floating. In some years they may be absent along major sections of the coast. The elevated ice deformation features which comprise the grounding persist later into the melt season than any other 'component of the fast-ice. In at least one year (1975), several of these large, grounded masses survived the summer and could be seen in the spring-summer fast-ice of 1976.

In 1973, 1974 and 1976 a coastwise parallel strip of open water and loose pack ice was present in August along most of the coast. In 1975, the fast-ice melt was retarded by extremely low summer temperatures, and the polar pack ice was held close to shore. This was also a year when several extensive, grounded ridge fields occurred in the eastern part of outer Harrison Bay to Cross Island. Landsat imagery from August and September, 1975, indicates these ice structures may have shielded the inner shelf from even more pack ice impingement than was observed. November, 1975, imagery indicates that the presence of these ice structures stabilized the incipient fast-ice sheet at a very early date.

B. Synoptic Climatology

1. Beaufort Sea

Daily MSL pressure grids for the sector 57°-80°N, 125°-170°W, have been classified for January 1966-August 1974 by Moritz (1978) using an objective technique based on Kirchhofer (1973). The method focuses on the location of pressure systems and their shape; the pressure gradient is normalized for each daily map removing intensity effects. Moritz derived 21 discrete characteristic patterns (CPS) which accounted for 97 percent of all days during the period. The order of identification of the types corresponds to their total frequency (i.e. CP1 is most frequent, CP21 least frequent). The most frequent patterns are those with low pressure over the southern part of the grid and highs or ridges to the north. Analyses of daily surface pressure charts in relation to the synoptic catalog of nominal pressure pattern types showed that some variation in qualitative features of the pressure field is to be expected among the individual daily grids grouped with a given CP.

The time series of nominal pressure patterns was analyzed for seasonal changes. In winter (mid-September to mid-May) CP1 dominates the surface circulation, with lows to the south and highs to the north (see Figure 1 a-d). CPS 3, 4, 7 and 9, which have their highest pressure somewhere near the northern coast with lower pressures to the southwest, south or southeast, are also important in winter. A pronounced shift in mean monthly pressure pattern frequencies occurs from mid-May to June, characterized by more frequent occurrence of CPS 2, 5, 6, 8, 10, 14, 15 and 21, and a corresponding decrease in frequency of the main winter CPS (see Figure 2). The summer regime, consisting of these patterns, is well developed during July through late August. This regime has frequent low pressure features over the central, western and northern portions of the grid sector. To the south, the Pacific High often extends northward as a ridge over the Gulf of Alaska at this season. The summer regime has a greater variety of patterns than does the winter regime. A second transition occurs from late August to mid-September, when the winter patterns begin to dominate again. During January, CPS 2 and 4 undergo a one-month frequency increase, leading to small "kinks" in the seasonal cooling curves at Barrow and Barter Island. This phenomenon is similar to, but less pronounced than the Antarctic coreless winter, and is caused by increased temperature advection when the two patterns occur.

On the interdiurnal time scale, persistence is the most important characteristic of the pressure pattern time series. All CPS persist significantly more often than at random. Non-persistence transition probabilities are generally too small to be of forecasting value, but are nonetheless highly significant in a statistical sense. Persistence is most pronounced for CP1 and for winter patterns in general. Non-persistence transitions indicate eastward progression of low pressure systems through the southern part of the grid sector in winter. Beaufort Sea highs and ridges often tend to be displaced south or southeast at this season. In spring, the southwest lows often move over central Alaska rather than skirting the state to the south, while in summer Pacific cyclone systems move northward along the west coast and into the Arctic Basin.

Coastal weather data are serially correlated on a day to day basis in the region, leading to reductions in the per-month degrees of freedom for the series. Nonetheless, daily temperature departures, wind speeds, and wind directions all show highly-significant associations with the CP categories in all seasons. Weather variables which have significant inter-CP differences in some, but not all, seasons include daily sky cover, dew-point depression and precipitation amount. Tests demonstrate conclusively that a portion of the variance in weather data series is due to the sea level pressure patterns.

Although any study of this size cannot completely characterize all aspects of the regional climatology, several important features were identified by our methods. In all seasons the surface wind directions are largely determined by the prevailing surface pressure pattern on the Beaufort Sea coast. Generally good agreement was found between the Barrow surface wind directions and the geostrophic directions on the CP synoptic maps. Daily temperature departures have three major regimes through the year. In winter the overall variance of temperature is largest. Screen temperatures are largely determined by the surface net radiation and the three dimensional temperature advection by the circulation. Thus extreme warmings are associated with influx of moist Pacific air, high wind speeds and relatively heavy cloud cover when CP2 occurs (see Table 2). By contrast, CPS 3 and 7 bring cold, clear, dry air from the central Arctic or Siberia, and cut off the Pacific influence at the surface. The normal winter pattern, CP1, lies between these two extremes with an intermediate rate of temperature advection from the south. Temperature departures with CP1 are, however, substantially closer to those of CP3 and CP7 than to those of CP2, which is a relatively rare pattern in winter. These relationships lead to a right-skew frequency distribution of screen temperatures in winter, especially in January when cP2 occurs more frequently.

During the spring transition the large-scale surface temperature contrasts between the Pacific heat source region and the Beaufort Coast are at an annual minimum, leading to a minimum in the variance of daily temperature departures. In some cases, notably CP6, the positive effects of large scale southerly advection begin to be balanced by local ocean/tundra heating differences. In summer these local contrasts are paramount, leading to positive temperature departures with offshore flow and negative departures for onshore flow (Table 3).. Since the surface winds are largely determined by the synoptic pressure pattern, there is a high degree of correspondence between the CPS and their temperature departures in summer. CPS 2, 4, 10, 15 and 21 have southerly components to their mean wind directions, bringing positive temperature departures and relatively large dew-point depressions to Barrow in July. By contrast, CPS 1, 5, 6, 8 and 14 have wind directions between west and east-northeast at Barrow, bringing negative temperature departures up to $-3^{\circ}C$ and near-saturated air.

The wind directions at Barrow are in general agreement with the CP synoptic map isobars in the majority of cases. As one might expect, wind direction is the most consistent weather characteristic of the CPS from season to season.

Barrow wind speeds show significant inter-CP differences in all seasons (see Tables 2 and 3). In winter speeds are low with the ridge patterns (CPS 3 and 7), while the cyclonic storms from the Pacific bring quite strong winds. These strong winds would be expected to develop in the presence of the strong surface baroclinicity which characterizes the region in winter. During the spring transition season most of the patterns have wind speeds around 5 ms^{-1}, but CP1 is one to two ms^{-1} faster. This increase occurs at the same time that the standard deviation of pressure over the daily maps is falling sharply for CP1, indicating weaker geostrophic flow. The implication is that the synoptic station network is inadequate to measure the true pressure gradient near the coast. This problem continues into the summer, when sea breeze effects are probably present (Moritz, 1977) , as indicated by strong easterly patterns ant? weak westerly patterns. Even during summer the patterns with northerly flow tend to have lower mean wind speeds. In the fall the cyclonic storms begin to become more intense, leading to higher winds.

Precipitation is primarily a function of the vertical motion field and the humidity of the air. During winter the patterns with advection from the Pacific tend to be cyclonic, implying positive vertical circulations near the Beaufort coast. Moist, marine air is brought into the region under these CPS. Thus CP2 is associated with measurable precipitation in over half its winter occurrences. However, the overall high frequency of CP1 and the small seasonal precipitation totals along the coast make CP1 the major winter precipitation pattern. By contrast, the west-coast cyclonic patterns are most frequent in summer, and the majority of the annual catch falls in association with these CPS during June-September.

In presenting these results and the synoptic catalog (available on tape via NODC), a qualification must be noted above the reliability of the pressure data over the Beaufort Sea. Comparison of the summer 1975 pressure data provided by AIDJEX with NMC analyses shows a significant degree of discrepancy (Wohl, 1978). However, when Wohl attempted to modify the synoptic classification using only data over northern Alaska and the Beaufort Sea, in order to eliminate the effect of Gulf of Alaska circulation systems on the CP categories, he found that the resulting revised classification was less satisfactory than the original one due to the poor data over the Beaufort Sea.

2. <u>Chukchi Sea</u>

An identified typing scheme was also developed for the Chukchi Sea for January 1946-August 1974 in order to ensure a sufficient extension to the west. The grid covers the ~~sector approximately~~ 57°N, 155°W--57°N, 175°E--77°N, 135°W--77°N, 155°E. A synopsis of the basic results and of the application of the catalog to an analysis of daily climatic data for Kotzebue is given in *Figures* 3 a-d, 4-7.

(i) Winter - Type 1 (Arctic High Pressure with subpolar easterlies at Kotzebue) is dominant, bringing near normal weather characteristics. Interruptions by anticyclonic (the most common) systems bring cold, dry weather to Kotzebue because they are associated with cold, continental air masses with weak northerly winds and little cloud cover which tend to reinforce the Arctic inversion. Cyclonic interruptions (less common) bring warmer than average, moist weather to Kotzebue because they are associated with warm maritime airmasses with strong southerly to easterly winds that tend to break-up the Arctic inversion and large cloud amounts that influence the net radiation budget by absorbing and re-radiating (terrestrial) radiation.

(ii) Summer - In summer there is a greater variety of types and the difference between cyclonic and anticyclonic types is not readily apparent. The main factor influencing temperature is geostrophic wind direction, with easterly winds causing continental outflow of warm air and westerly winds causing cool air advection from the Chukchi Sea. Because ice conditions are closely related to temperature conditions, warm types with easterly flow (1, 2, 13, 17) are probably important in helping force summer ice break-up. Cold westerly types (3, 10, 15) are probably important for delaying that breakup. Type 3 which is closest to the mean pressure pattern is the most common type in July.

During summer, a mean storm track is established from south to north up the Bering Sea and through the Bering Strait, following the northwest coast of Alaska in the Chukchi Sea. Hence, summer is a time of heightened cyclonic activity, with cyclonic types 2, 7, 12, 17 bringing considerable precipitation. It is likely that the role of open water in the Bering and Chukchi seas is important in supplying latent heat and moisture to storms moving along this track, which are less frequent during the frozen winter period.

A relationship between the onset of "monsoon" westerly winds and accumulated thawing degree days (TDDs) in summer has been established (Figure 8). Probably because of the influence of interior high temperatures and resultant thermal low, westerlies tend to blow inland at Kotzebue during summer, unless interrupted by strong opposing pressure types. The earlier these winds set in, the lower the total TDDs at Kotzebue.

Based on analyzes for Kotzebue described in the Annual Report for 1978 (p. 49), a general model of a cold July on the Chukchi Sea coast can be outlined.

1) Major cyclonic types (2, 7, 12, 17) decrease in frequency, from 77 days in 7 warm Julys to 38 days in 7 cold Julys, indicating that the normal storm track up the Bering Sea, Bearing Strait, and eastern Chukchi Sea does not become well established.

2) Marginally cyclonic types increase (types 5, 10, 11, 15) in frequency from 29 days in warm years to 57 days during cold years. This may indicate a shift of the normal storm track to. the east, over continental Alaska. This track tends to advect cool air from the Chukchi Sea to Kotzebue by reinforcing the prevailing NW and N winds.

3) A logical reason for such a shift would be the establishment of a mean upper trough over the Chukchi Sea tending to "steer" surface storms to the east of Kotzebue. Such a trough would also bring cold Arctic air over the Chukchi Sea, tending to delay ice breakup. It would be associated with upper divergence over the Beaufort Sea, which favors the development of lower pressure in this key area. Low pressure in the Beaufort Sea brings northwest surface flow at Kotzebue, again strengthening the prevailing westerlies.

4) Delayed ice breakup in the Chukchi Sea tends to bring about the lower sea surface temperature and cooler conditions in general at Kotzebue, as indicated by the decrease in average temperature of most of the other types at Kotzebue.

There is some relationship between the winds over the Chukchi coast and ice conditions at Barrow. The five years of earliest westerly onset were also the years with most severe summer ice conditions at Barrow. The causal mechanism behind this association is not yet established, but the relationship has some predictive value. If the westerlies set in prior to May 4 at Kotzebue, it is likely to be a severe ice summer on the Beaufort Sea coast.

The warmest weather at Barrow during summer is associated with Chukchi types 2 and 12, which are characterized by cyclones in the Bering Sea and Bering Strait region, which steer very warm air toward Barrow from the North Pacific. These types occur on about 30 percent of the days during warm July, but only about one-half that during cold Julys. Types 3 and 10 are the cold types which occur on 26 percent of the days during cold

Julys and only one-half that during warm Julys. They are characterized by cyclones in the Beaufort Sea that steer cold air southward and westward from the Arctic pack ice to Barrow.

C. Climate-Ice Interactions

1. General Relationships

A central objective of the project has been to determine the role of the seasonal climatic regime and synoptic weather events on the course of the fast ice decay. This has included case studies and statistical analysis of long-term climatic data at Barrow. The details of our results are presented in Appendices 1-3 and only a brief summary is given here.

From analysis of Landsat imagery and Barrow temperature data the following general relationships have been established with thawing degree-days (TDDS) for the Beaufort Sea ice off Barrow:

	TDDs (°C)	Ice Event
(i)	<55	initiation of pending and rapid thawing of ice
(ii)	55 - 140	- initial breakup, some open water
(iii)	140 - 220	- fast ice largely gone, melting on pack ice
(iv)	220 - 300	- pack ice retreats, up to 80 km north of Pt. Barrow
(v)	>300	pack ice retreats more than 80 km

From more limited data for Kotzebue and ice conditions off Kivalina, *in situ* melt begins with about 10 TDDs, first breakup with 55, and the nearshore zone is largely clear with 200 TDDs.

The frequency of these categories shows a significant change over time, based on climatic data at Barrow:

TDD categories	1921 to 1952	1953 to 1975
(i)	0	0
(ii)	1	1
(iii)	3	10
(iv)	12	4
(v)	16	8

The number of summers in which the pack ice did not retreat jumped from 4 in 32 years (12%) to 11 in 23 years (48%) in the last 55 years. There has been an average loss of 37 TDDs (a decrease from 311 for 1921-52 to 274 for 1953-75) or about 0.5°C in the mean summer temperature over the same time intervals.

Since Landsat data on ice conditions have only been examined for the 1973-76 summers, it is important to compare the climatic conditions during these years with long-term averages. This is done in Table 4, which shows mean thawing degree-days totals for Kotzebue, Barrow and Barter Island and a ranking of the 1973 to 1976 summers in terms of standard deviation (S.D.) departures. At Barter Island, all four years are within the ± 1 S.D. range about the mean.

Analysis of early weather records at Barrow for 1882, 1883, 1902, 1903, 1911, and 1916, and comparison with the interpretations of data on ice conditions in ships' logs by Hunt and Naske (R.U. #261) indicates mixed results. Both sources agree on light-ice conditions in 1902 and 1911, the data for 1883 and 1916 are too sparse to make definitive comparisons, and for 1882 and 1903 there appears to be some element of disagreement.

Regression analysis of summertime climatic parameters and pack ice retreat by mid-September tabulated by Barnett (1976) shows that geostrophic winds are not the best indicator of the distance off Barrow to the limit of 4/8 ice concentration. Surface wind direction makes a small contribution to the variance, but thawing degree-day totals alone account for 65 percent of the variance of ice distance. This dominant temperature effect makes the role of other variables seem largely irrelevant at the present stage of our understanding of ice decay and breakup processes.

This finding raises the question of the role of wind direction in determining the summer temperature. An earlier analysis by Weaver (1970) shows that at Barrow, southerly winds bring significantly higher summer temperatures (10.6°C in July 1966) than onshore winds (2.7°C). It remains to be determined how much of the temperature-explained variance derives from this effect. Also, it is not clear how far the occurrence of open water off Pt. Barrow helps to determine the station temperature instead of the reverse, as we are assuming. Since water temperature remains close to freezing point the former effect should be limited.

2. Synoptic Climatology - Ice Interactions

The synoptic typing catalog developed for the Beaufort Sea area has been examined by Wohl (1978) in terms of its usefulness for discriminating coastal ice conditions. Individual synoptic types and groups of types, according to their geostrophic wind direction at Barrow, have been analyzed against Barnett's index[1] of ice conditions off Barrow on September 15 during 1953-77 by stepwise regression. Groups of northerly and southerly flow types account for about 42% of the variance but their average summer frequency is only 6 and 17 days, respectively. Re-definition of the circulation patterns using only grid points north of 65°N

[1] This score is the sum of the distance from Pt. Barrow to the ice edge and to the boundary of 4/8 ice concentration on September 15, the initial date that the sea route from Barrow to Prudhoe Bay has ≤ 4/8 ice, the number of days this route. is ice free, and the number of days it has ≤ 4/8 ice.

and subsequent re-analysis along the same lines gave no significant improvement. Apart from the problems of unreliable pressure data over the Beaufort Sea already noted, there is the basic problem of attempting to determine the net effect of the season's climatic characteristics on ice conditions late in the season. While individual seasons, such as 1975, may show clear relationships to atmospheric circulation in terms of pack ice movement (Wendler and Jayaweera, 1976) , most seasons show less persistent circulation patterns.

Preliminary work by Warmerdam on 500 mb pressure patterns and May-September air mass characteristics at Barrow (based on mean daily equivalent potential temperature at the surface) suggest some potentially useful relationships with ice conditions at Barrow. These results are as follows:

(1) Air mass frequency is closely associated with ice conditions. Severe ice years occur in summers with a dominance of Arctic air at Barrow (80% in August) , while light ice years occur in association with infrequent Arctic air (20% in August) and its displacement by warmer Pacific air masses from the south .

(2) August is the key month. There are large significant differences in Arctic air frequency during this month between severe and light ice years. Differences are also notable in July, but are not as great, and there are no significant differences in May, June, or September. This implies difficulty in long-range prediction of ice severity.

(3) The 500 mb patterns responsible for displacing Arctic air with Pacific air seem to be mostly those with ridging over Alaska and/or Canada, leading to southerly flow over the North Slope. If such ridging isnot present during August, it will be a moderate to severe ice summer.

(4) Severe ice years seem to be associated with the formation of a large upper trough over the Alaskan region, effectively blocking Pacific air from reaching the North Slope.

3. Polynyi Near Point Hope

A special analysis of the occurrence of polynyi in the" vicinity of Point Hope on Chukchi Sea coast has been carried out. Areas of open water and thin ice have been mapped from Landsat imagery for March-June 1973-77 (Table 5). The thin ice areas show up by their proximity to open water and from their usually much lower reflectance.

The development of polynyi and interannual differences in extent have been examined in relation to wind and temperature data. Onshore and alongshore components of geostrophic wind are determined from MSL pressure at six NMC grid points in proximity to Point Hope. Temperature data are for Kotzebue, but should be generally representative.

Rapid polynya development in spring is favored by strong offshore winds causing frictional divergence. Both 1974 and 1976 illustrate this effect (Table 5). The average wind is NE, 9.5 m 5^{-1} in March 1974. The decrease in size from April to May apparently reflects the decrease in wind speed and the small accumulation of TDDs. The expansion during June, however, seems to be related to the rapid increase in temperature.

The reduction in polynya size from March to April 1976 is probably attributable both to the slight decrease in wind speed and to the low temperatures. From April to May, wind speeds show some increase and TDDs are also accumulating.

It is concluded that early polynya development is favored by strong offshore (Northeasterly) winds. This dynamic effect seems to be important if wind speeds increase during the season. Advection of warm air from the land appears to become equally important as the season progresses, but there are too few cases at present to quantify this effect.

VII. DISCUSSION

The picture of the ice regime and its response to climatic conditions developed in this study must still be regarded as tentative. The period of detailed record provided by the Landsat imagery is too short to be confident that a range of conditions representative of, say, a 10-20 year period has occurred. Several other factors introduce additional uncertainties into the interpretations. The infrequent Landsat coverage, due to the orbit mode and cloud cover, makes the timing of many ice events and the melt stages imprecise. Moreover, the limited ground truth available to assist the interpreter makes the reliability of the ice maps dependent on subjective judgement. It is believed that the mapping was at least internally consistent for each coast, since the interpretation was carried out in each case by a single individual with field experience in the area in summers 1975-77. Another problem, already referred to, is the unreliability of the pressure data in the Beaufort Sea.

In terms of analytical methods, it is considered that the combination of synoptic and statistical climatological approaches has proved worthwhile.

The synoptic catalogs provide a useful statistical description of the dominant seasonal circulation patterns and their weather characteristics in the two areas. The fact that a simple temperature index proves more effective in accounting for ice variability than the synoptic type frequencies reflects several problems. First, there is only one value of the ice index per year to be related to the total effect of a large complex of weather conditions over the summer, some positive, some negative. Second, each type is subject to internal variability in the actual weather conditions that occur, especially as no account is taken of pressure gradient. Third, the type catalogs are imperfect descriptions of the actual pressure fields due to the basic data limitations over the Beaufort and northern Chukchi seas. Even so, the type catalogs and the quantitative type descriptions provide a basis for assessing the likely effect of given circulations on the coastal climate. It must also be cautioned that the statistical associations imply linear relationships whereas most of the processes involve complex feedbacks and are likely to be non-linear.

Ice decay and breakup is determined partly by the ice history, in terms of the frequency of grounded ridges. River flooding causes local polynyi to develop. These assist the melt and breakup process by facilitating movement, which may initially be shoreward. However, it remains uncertain as to the relative importance of thermodynamic processes, especially associated with warm air advection, and mechanical wind stress on the fast ice breakup. Obviously warm offshore winds (southerly on the Beaufort Sea coast, easterly on the Chukchi Sea coast) will assist in accelerating the melt process and in breaking off ice floes if there is a flaw lead in the shear zone. The statistical relations, at least, imply that the thermal effect is more important, but more work is needed to examine this question of process thoroughly.

On the time-scale of a few days, for example, there is a good correspondence between the timing of breakup between Pt. Barrow and Cape Halkett, as determined from the Landsat imagery, and the occurrence of southerly geostrophic winds. Beaufort synoptic types CP2 and 5 occur on a majority of these days. The relationship is less clear, however, if examined in terms of observed southerly surface winds.

Relationships between the weather characteristics and pressure patterns suggest some possibly useful applications. The establishment of the Pacific High in its summer position should lead to the regime dominated by Beaufort type CP2. If monthly forecasts of the pressure field can be made by numerical, analog, or other means, then a forecast for the early displacement of the high in spring implies an early onset of southerly winds, positive temperature departures, and possibly a light sea ice year along the coast. The occurrence of high winds in winter with incursions of cyclonic patterns implies that the near-shore ice may be subject to false freezeups and subsequent disturbance by such storms before, say, January or February. A case of such ice disruption has been documented by Shapiro (1976) for December 1973 near Barrow. The general seasonal character of pressure pattern occurrence, and their associated weather characteristics will also be useful as an introduction to forecasters in the region, although the major application of the data should be as an information resource for planning and decision-making involving the Beaufort Sea Coastal region.

VII. CONCLUSIONS

The results of this project allow two broad sets of conclusions to be drawn. The first group are direct products of the ice mapping and climate-ice interaction studies. The second set are more general, tentative, inferences of significance for planning with regard to offshore petroleum development.

A. The Seasonal Fast-Ice Regime

The results of our program, combined with other OCS studies, provide a scenario of the fast-ice regime that can serve as a framework for seasonal scheduling of operations in the nearshore zones (see Appendix 1 for details).

1. Beaufort Sea Coast

(i) new ice formation - late September/early October

(ii) first continuous fast-ice sheet - mid/late October
Unstable outside bays and the barrier islands

(iii) extension and modification of fast-ice - November to February

No direct observations cover this period. The general sequence involves:

- seaward fast-ice progression of the ice edge
- ridging of successive ice edges
- incursions of older ice
- grounded ice masses, formed *in situ* or driven shoreward

(iv) stable fast-ice inside about the 15m isobath - February to April/May

(v) estuarine flooding of ice - late May

(vi) puddling on ice - early June

(vii) melting and weakening of ice - June (Attached ice decays April/June)

(viii) breakup - late June to August

(ix) nearshore area largely free of fast-ice - early August Some deep-draft older ice and ridge fragments remain in the nearshore zone.

2. Chukchi Sea Coast

The fast-ice on the Chukchi coast is generally less extensive than on the Beaufort Sea coast (see Figures in Appendix 1). The sequence is similar to that above except that, for the central section, freeze-up occurs about two weeks later, and breakup 3-4 weeks earlier. Sections such as Peard Bay, in the north, where the coastline is oriented roughly east-west and there are barrier islands, tend to have breakup characteristics similar to the Beaufort coast east of Barrow. Polynyi are a prominent feature south of Point Hope in spring-early summer when they assist in accelerating the breakup. The fast-ice/pack-ice boundary south of Barrow is the frequent site of a flaw lead in winter and the ice in this sector is generally less stable and more subject to disruption and ridging by pack-ice pressure.

B. Ice Conditions and Climatic Effects

(1) Summer temperature conditions, as indicated by accumulated thawing degree-days, account for 65 percent of the variance in the distance off Pt. Barrow of the southern limit of 4/8 concentration of pack-ice on September 15. If windspeed and pressure data are incorporated in the regression, 80 percent of the variance is accounted for. Variability in ice extent by late summer is related to the sea level pressure distribution, surface wind direction at Barrow, and maximum accumulated thawing degree days at Barrow. Winds are more frequent from the south-southeast (135°-1950) during light-ice summers while winds from the north-northeast (345°-45°) are more frequent during severe ice summers (Rogers, 1978). These winds and pressure distributions are probably indicative of the fact that warm and cold air advection over the ice plays a primary role in determining whether a light- or severe- (respectively) ice summer will occur. This in turn is reflected in the thawing degree day accumulation which is the parameter most highly correlated to the distance which the ice retreats northward. (See Appendix 2.)

(2) An accumulation of 140-220 thawing degree days (°C) is required to remove the fast ice and 220-300 TDDs for open water to extend up to 80km off Pt. Barrow on September 15. Along the Chukchi coast, the ice data are less precise as to the timing of events due to the satellite coverage. For the Kivalina sector, using Kotzebue temperatures, approximately 200 TDDs are required to remove the fast.

(3) The high correlation between accumulated TDDs and ice retreat has been used by Rogers (1977) to develop the basis of a scheme for long-range forecasting of ice conditions in summer-early autumn along the Beaufort Sea coast (Appendix 3). The results suggest that forecasts could be made with reasonable success based upon persistence of air temperature anomalies from month to month. Persistence occurs between all months with greater frequency than would be expected by chance. In general, the anomaly of air temperature in July is most likely to recur in August, and the anomaly in August is very frequent again in September.

(4) The synoptic pressure pattern types can be characterized seasonally in terms of broadly distinctive combinations of temperature and wind conditions. Thus, CP 1 for the Beaufort Sea sector represents a pattern of polar easterly circulation, resembling the mean winter pattern, with strong NE winds and temperatures about or slightly below average. Types CP 2 and 5, which are frequent summer patterns, give rise to southerly geostrophic (southwesterly surface) winds and positive temperature departures. The summertime shift to these types is the underlying determinant of ice breakup. The available data indicate that frequencies of surface types with northerly and southerly flow components account for about 40% of the variance in the Barnett ice index. However, the TDD index is a simpler and more successful descriptor. Preliminary analysis

of mid-tropospheric circulation patterns suggests that these may be a more useful index than surface pressure fields. Further work on this would be necessary to provide definite results.

(5) Climatic data at Barrow indicate a drop in summer temperature of about 0.5°C for 1953-75 compared with 1921-52. Correspondingly, the number of summers in which >220 thawing degree days (°C) were attained has declined from 88 percent for 1921-52 to 52 percent for 1953-75. This implies that fewer summers with good shipping conditions have been experienced since the 1950's compared with the three preceding decades. In climatic terms, at least, the 1975 summer was not a rare event. The limited climatic data for the 1892-1916 interval at Barrow suggest that ice conditions inferred from ship's logs should be interpreted with caution.

(6) The movement of pack ice, or broken fast-ice, along the Beaufort Sea coast in summer is almost always in the same direction as the wind at Barrow and Barter Island, even though the moving ice may be hundreds of kilometers from these stations. However, the ice at Barrow moves with lighter winds than at Barter Island. Movement and breaking of ice observed on Landsat imagery in the vicinity of Barter Island usually occurs with wind speeds averaging twice those during ice motion off Barrow. This may relate to the tendency for more open water in the Barrow area and the ice outlet via the Chukchi Sea.

C. <u>Ice Hazards in Relation to Offshore Petroleum Development</u>

(a) Ice deformation features. Ridges and hummocks show more or less preferred locations from year to year (cf. maps prepared by W. Stringer RU #257), probably in relation to the location of shoals (see Reimnitz, et al., 1978). Examples are: offshore and west of Barter Island, in a line from Narwhal Island to a point approximately 80km due north of Atigaru Point in Harrison Bay, and approximately along the 20m isobath arcing around Pt. Barrow in the Chukchi Sea and Beaufort Sea. These areas are the scene of enormous shear and pressure forces, most of which seem to occur during the dark period November through February.

The edge of contiguous fast-ice appears to be displaced progressively seaward through the winter months, based on interpretation of ice edges and puddling features on summer imagery. Each successive winter ice edge can be a site for ice deformation so that large grounded ice masses can occur well inside the 20m isobath. In general, however, the areal extent and intensity of ice deformation seems to be greatest near the late-winter fast-ice edge in the so-called stamukhi zone (Reimnitz, et al., 1978). This may be a consequence of the involvement of more massive polar floes and thicker first-year ice in ridge formation late in the season. Our case-study of ridging off Oliktok in late March - early April, 1975 illustrates the anomalously large and well-grounded field of shear ridges that may form in this manner.

The implication is that permanent offshore structures may be subject to relatively large ice forces, even well inside the 20m isobath, but these forces would occur further seaward by late winter. Recent work by Kovacs and Sodhi (1978) also shows that the entire Beaufort Sea and northern Chukchi Sea coasts may be subject to shore pile-up or ride-up, especially in spring and autumn. Such events may occur within 15-30 minutes with ice mounting steep coastal bluffs up to 10m high.

(b) Grounded ice. As noted above, remote sensing data can be used to locate well-grounded ice because it remains *in situ* late into the melt season. This type of ice is very discontinuous along the coast. During the decay season, therefore, under-ice oil spills occurring within the fast ice zone would not necessarily be contained within a band of grounded ice parallel to the coast. Nevertheless, the elongate ridges which parallel extensive segments of the Beaufort Sea coast in late winter have keels extending well below the level ice, even though they may be floating or only weakly grounded. These ridges might be effective in temporarily containing most of an under-ice oil spill during February through May. Such trapping capability would rapidly diminish after late June as the fast ice begins to disintegrate leaving only well-grounded ridges *in situ*. This decay date also marks the end of the period when trapping could occur in the irregular bottom topography of the floating fast ice.

Our mapping has shown that well-grounded, deformed ice masses are occasionally found in waters $\leq$ 10m deep. Structures and lines on the near-shore bottom must be able to withstand the forces generated by such features and associated bottom scour, even though the frequency and intensity of such events are much less than in the *stamukhi* zone.

TABLE 1. AVERAGE SEASONAL REGIMES IN ALASKAN SHOREFAST ICE

Ice Phase	Central Beaufort Sea Coast	Central Chukchi Sea Coast
New ice forms	3 Oct.	10 Oct.
First continuous fast ice	Mid October	Early November
Extension/modification of fast ice	Nov. - Jan./Feb.	Nov./Dee. - Jan./Feb.
Stable ice sheet inside 15 m isobath	Jan./Feb. - Apr./May	Feb. - Apr./May
River flooding fast ice	25 May	1 May
First melt pools	10 June	10 May
First openings and movement	30 June	10 June
Nearshore area largely free of fast ice	1 August	1 July

[1] These dates are based on available Landsat imagery for 1973-1977. An identifiable event may occur anywhere between the dates of available clear frames which bracket the latest date of recognized non-occurrence and the earliest date of its identified occurrence; the average of these dates is used here.

TABLE 2

JANUARY CP WEATHER CHARACTERISTICS

CP	dT1 (°C)	E i -	WD (°)	U (m/s)	SC (1/10)	dTD (°C)	r* (mm)	%-1 (%)	%-2 (%)
1	-1.8	-2.4	?3	5.6	5.2	4,5	66.3	20	11
2	+13.5	+15 ,1	226	795	799	2.3	46..2	14	58
3	-3,6	-3,4	304	4.0	5.2	4.1	19.0	6	11
4	+3.0	+2.8	104	5.4	5.9	3*9	46.5	14	19
5	+2.7	+5.6	267	6.9	6.1	5.3	29.5	9	29
6							16,0	5	46
?	-2.5	-3*3	315	3.2	4.1	3.8	0,5	0	2
8							8.1	2	53
9	+1.4	-1.5	154	5,6	6,4	3.5	26.2	8	23
10							41.9	13	44

*Precipitation data are for season I (January-March) rather than for January ,

TABLE 2a

KEY FOR WEATHER CHARACTERISTIC TABLES

Symbol	Explanation
CP	Characteristic pattern
$\overline{dT1}$	Mean of the daily temperature departures at Barrow
$\overline{dT2}$	Mean of the daily temperature departures at Barter Island
$\overline{WD}$	Mean of the daily wind directions at Barrow
$\overline{U}$	Mean of the daily wind speeds at Barrow
$\overline{SC}$	Mean of the daily sky covers at Barrow
$\overline{dT_D}$	Mean of the daily dew point depressions at Barrow
r	Total precipitation catch (water equivalent) at Barrow 1956-1974, for the given season and CP
%-1	r as a percentage of the unstratified seasonal catch at Barrow, 1956-74
%-2	Number of days with measurable precipitation at Barrow, as a percentage of the number of daily occurrences of the given CP

TABLE 3

JULY CP WEATHER CHARACTERISTICS

CP	$\overline{dT1}$ (°C)	$\overline{dT2}$ (°C)	$\overline{WD}$ (°)	$\overline{U}$ (m/s)	$\overline{SC}$ (1/10)	$\overline{dT_D}$ (°C)	$\overline{r^*}$ (mm)	$\overline{\%-1}$ (%)	$\overline{\%-2}$ (%)
1	-1.7	-1,5	68	6.3	6.4	1.7	49.5	5	15
2	+1.0	+1.6	227	5.1	8.5	2.1	329.7	35	46
4	+2.0	+0.2	89	5.5	6.9	2.5	28.4	3	21
5	-2,1	-1.4	262	5.0	8.9	1.8	115.6	12	46
6	-0.3	-1.2	71	5.4	8.0	1.8	77.7	8	34
8	-2.5	-3.0	9	4.6	8.9	0.9	64.3	7	39
14	-3.2	-2.6	308	3.9	8.2	1,4	15.0	2	30
15	+1.3	+0.1	196	5.0	8,9	2.1	156.0	17	54
21	+0.6	-1.8	91	5.3	8.0		1.5	0	23

*Precipitation data are for season IV (July-August) rather than for July .

TABLE 4. AVERAGE THAWING DEGREE-DAYS (°C) AND 1973-76 SUMMER CONDITIONS

Parameter	Kotzebue	Barrow	Barter Island
Mean TDDs	1080 (1943-76)	296 (1921-75)	324 (1948-75)
S.D.	113	101	98
Median	1059	275	317
±1 S.D. range	967-1193	194-397	226-422
1973	below avg.[1] (971)	above avg. (358)	above avg. (398)
1974	above avg.[1] (1170)	above avg. (364)	below avg. (328)
1975	>2 S.D. colder (845)	>1 S.D. colder (192)	below avg. (256)
1976	near avg. (1086)	near avg. (273)	near avg. (320)

[1]Denotes a total within 1 S.D. of the mean value.

TABLE 5. POLYNYA EXTENT AND CLIMATIC PARAMETERS

Year	Date	Polynya Area (Km^2)	Monthly Rate of Change (Km^2)	Cumulative TDDs (^oC)	Mean Vector Wind for NMC Grid Points Near Point Hope (ms^{-1})
1973	11 April	900		1	ENE 7.5
	17 May	1025	+ 125	53	ENE 6.5
1974	20 March	2280		0	ENE 9.5
	7 April	4125	+1845	0	ENE 11.0
	*13 May	1450	-2675	26	ENE 5.5
	17 June	4500	+3050	162	E 1.5
1975	*12 April	560		0	E 3.0
	*16 May	1290	+ 730	30	ENE 6.0
	*3/5 June	1650	+ 360	127	NNE 2.0
1976	17 March	4235		0	E 5.0
	22 April	475	-3760	2	ENE 4.5
	10 May	1850	+1375	35	NE 6.0
	15 June	2660	+ 810	162	SE 0.2
1977	17 April	663			ENE 3.0
	23 May	2113	+1450		E 4.0

‘Restricted coverage by satellite, polynya area may be underestimated .

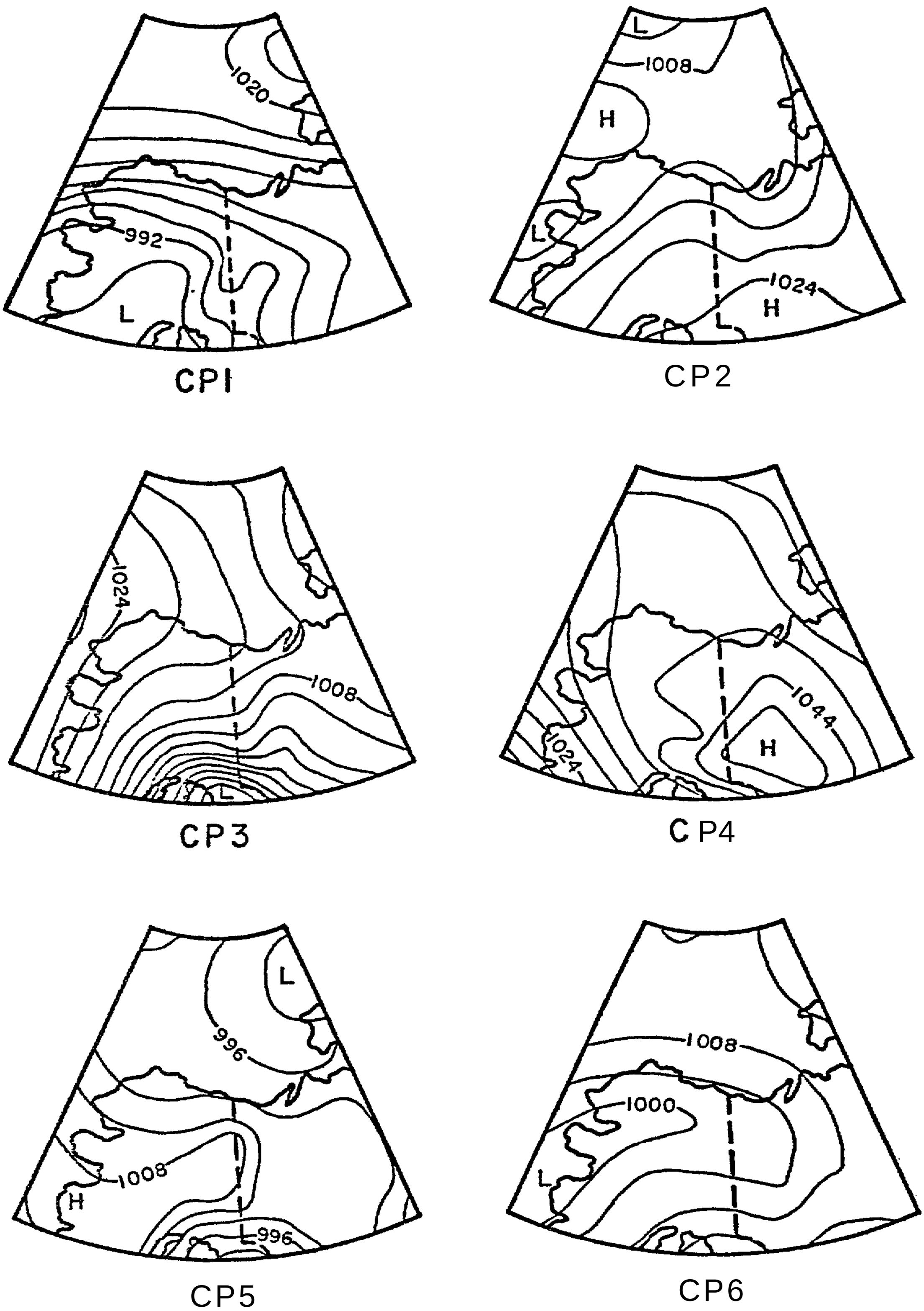


Figure 1a. Characteristic Patterns 1-6

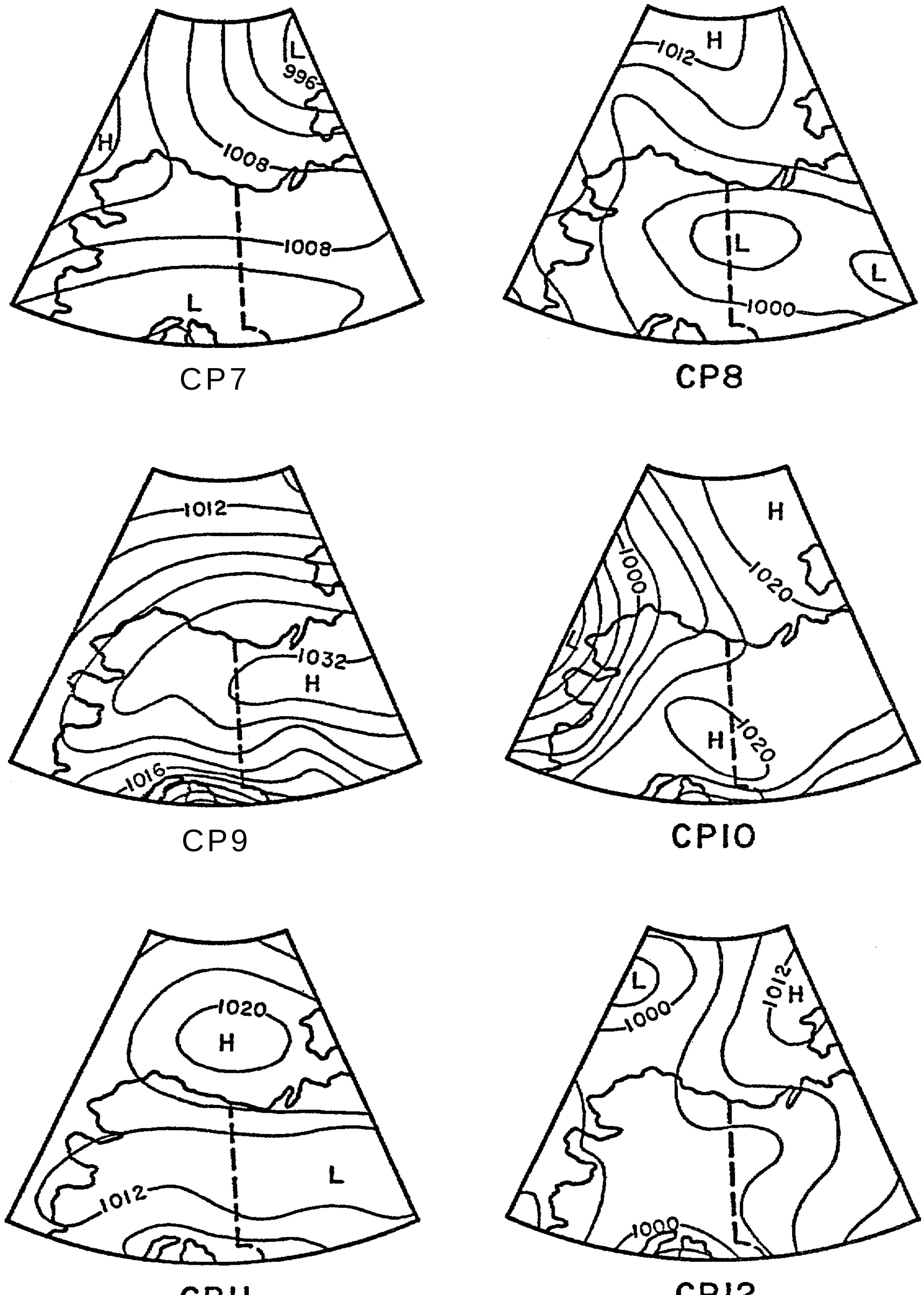
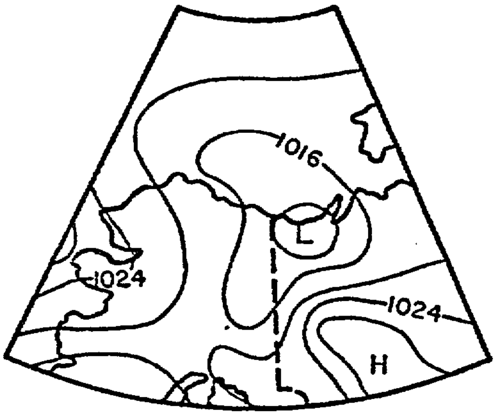
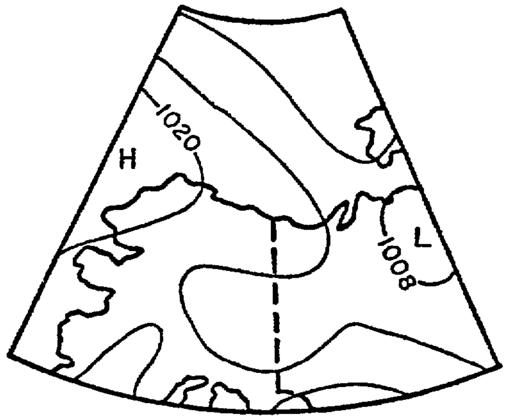


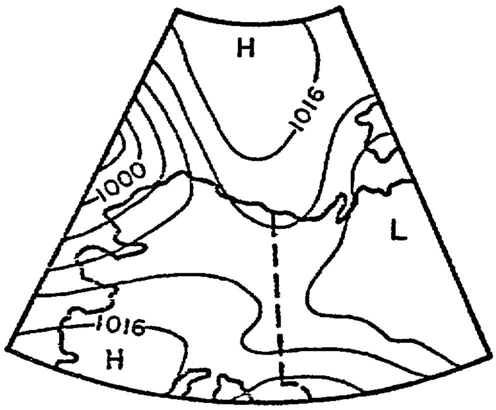
Figure lb. Characteristic Patterns 7-12



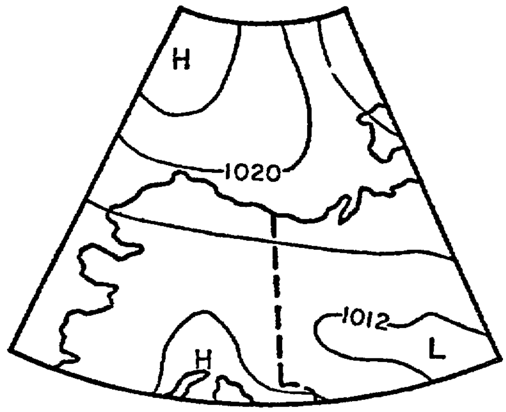
CP13



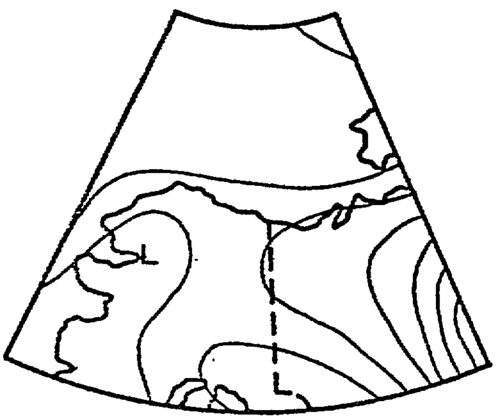
CP14



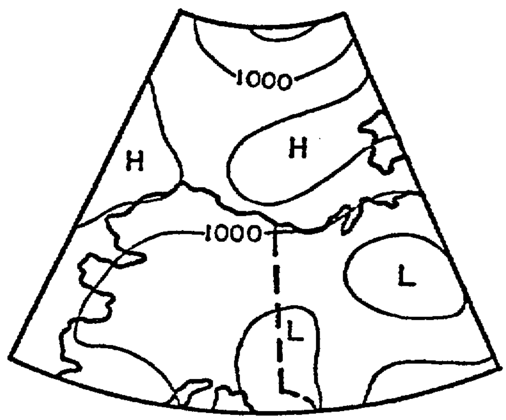
CP15



CP16

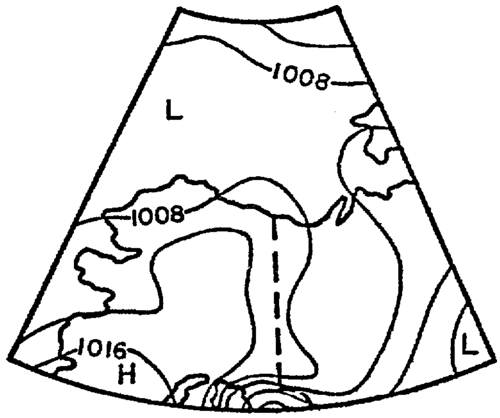


CP17

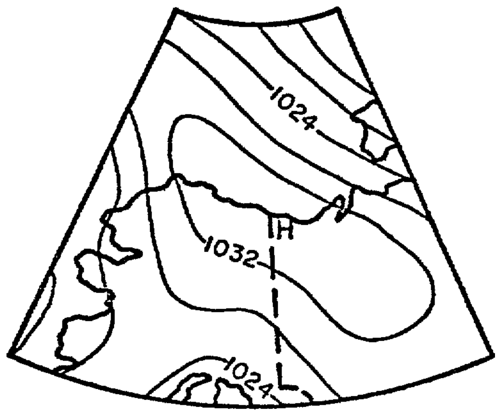


CP18

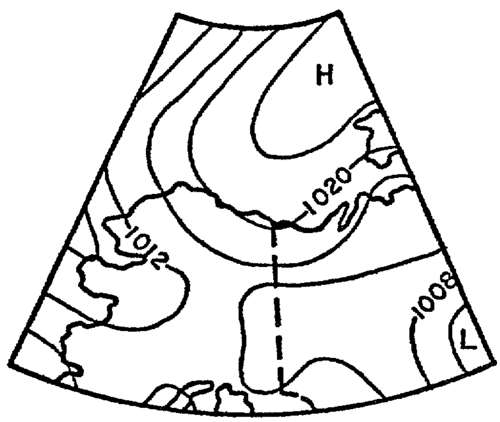
Figure 1c Characteristic Patterns 13-18



CP19

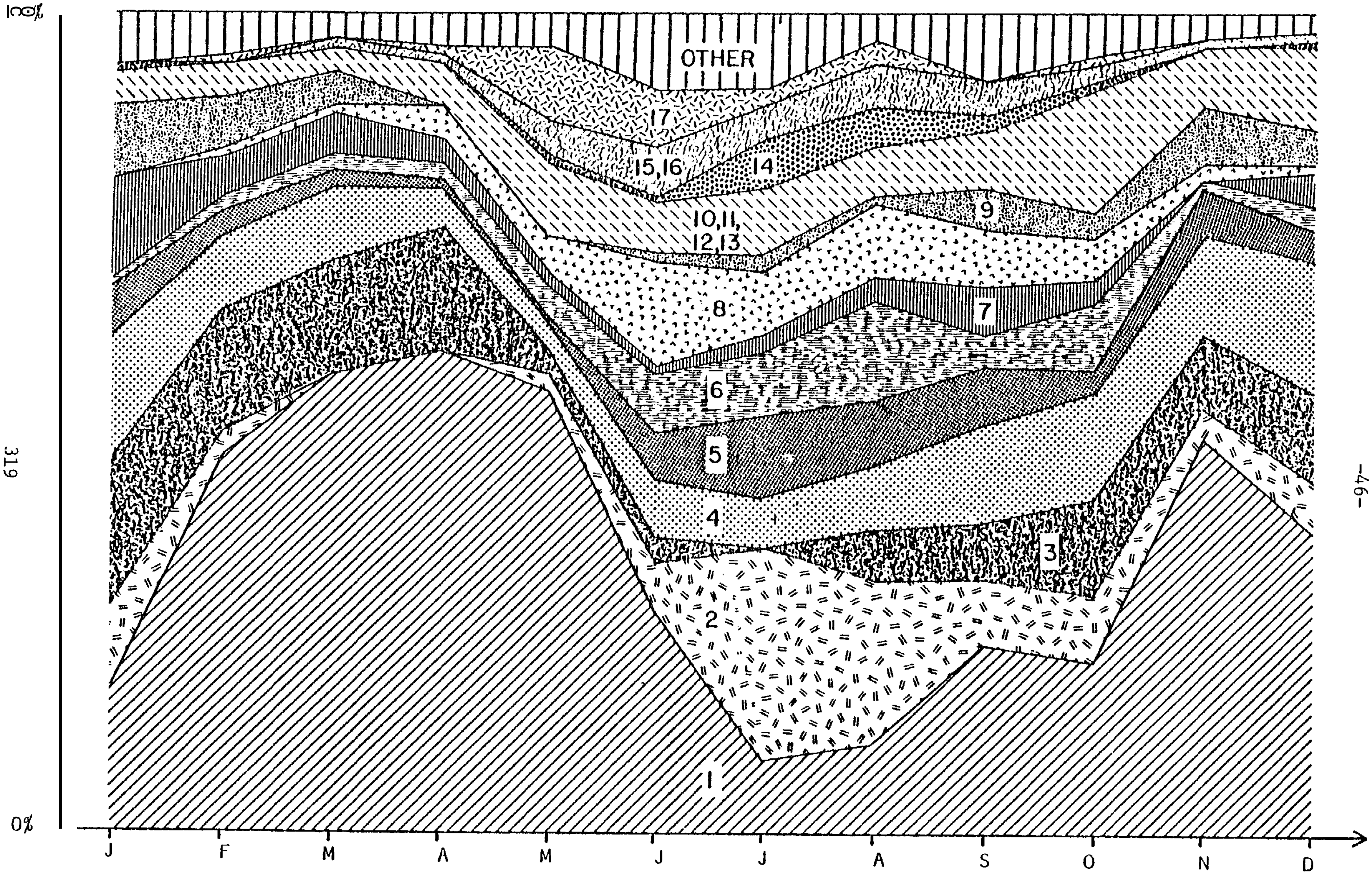


CP20



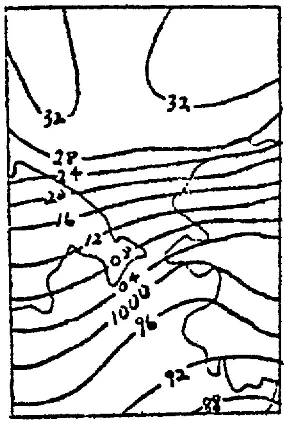
CP21

Figure 1d Characteristic Patterns **19-21**

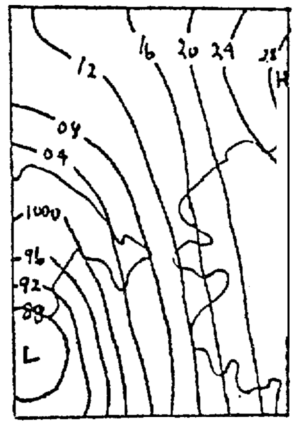


FREQUENCY OF BEAUFORT SYNOPTIC TYPES

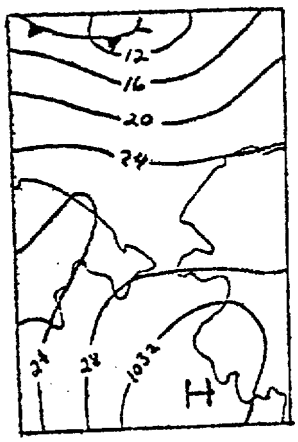
Fig 2. ·September, 1968 ⊙ August, 974



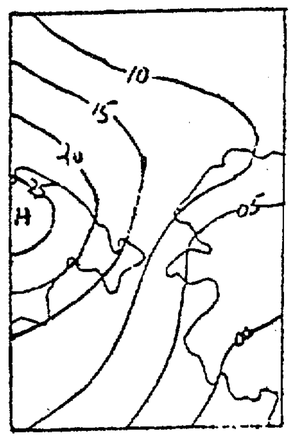
Type 1. 14 March 1970



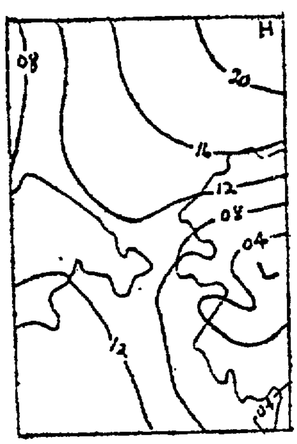
Type 2. 7 August 1968



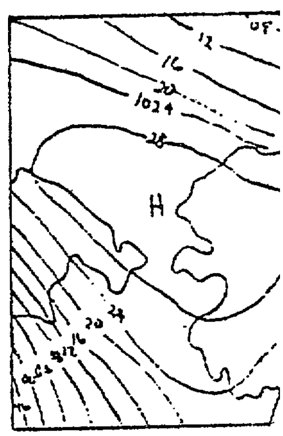
Type 3. 20 March 1967



Type 4. 2 February 1961

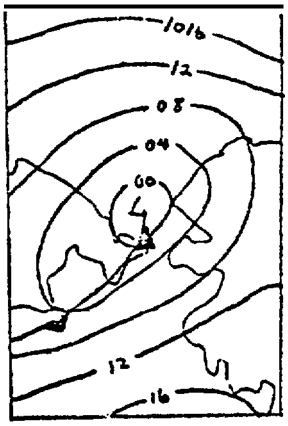


Type 5. 23 June 1969

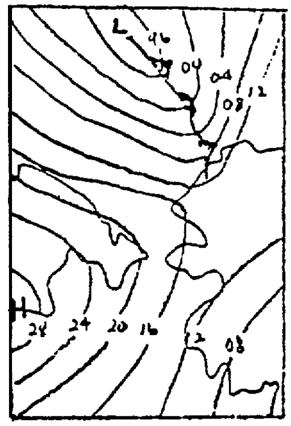


Type 6. 12 March 1955

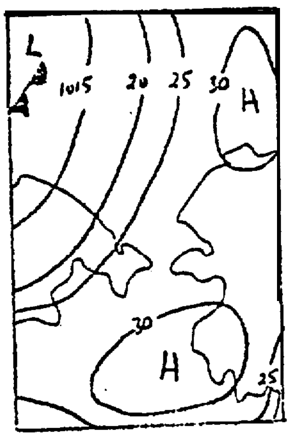
Figure 3a Chukchi Synoptic Types 1 - 6 (isobars in mb, omitting 1000 or 900)



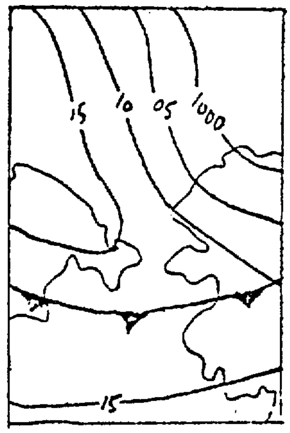
Type 7. 16 July 1966



Type 8. 26 September 1957

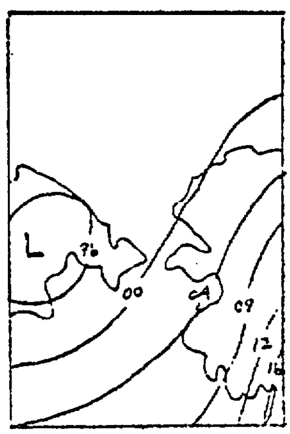


Type 9. 17 April 1948



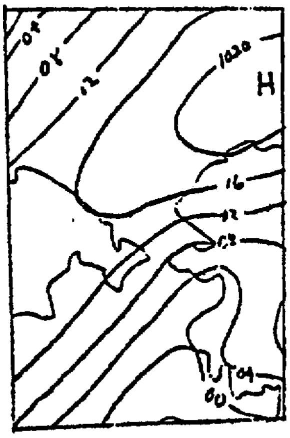
Type 10. 28 August 1948

Type 11. 4 February 1955

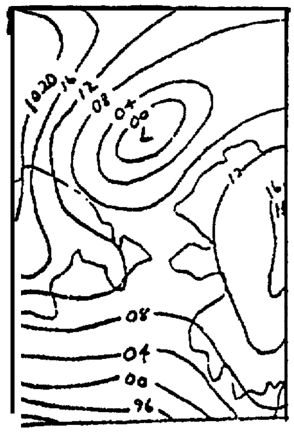


Type 12. 8 September 1946

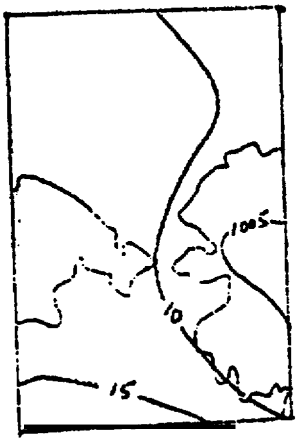
Figure 3b Chukchi Synoptic Types 7 - 12 (isobars in mb, omitting 1000 or 900)



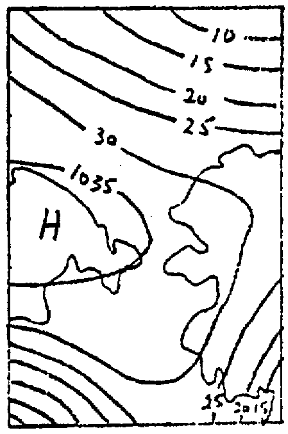
Type 13. 16 June 1969



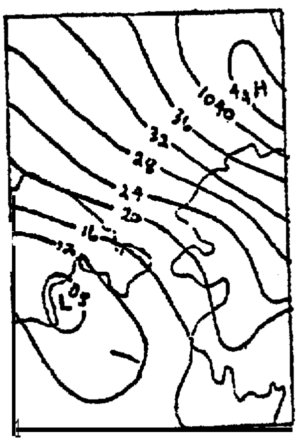
Type 14. 19 December 1966



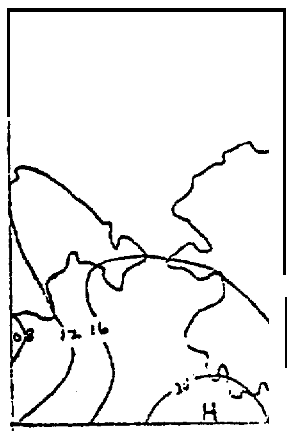
Type 15. 16 June 1960



Type 16. 4 March 1956

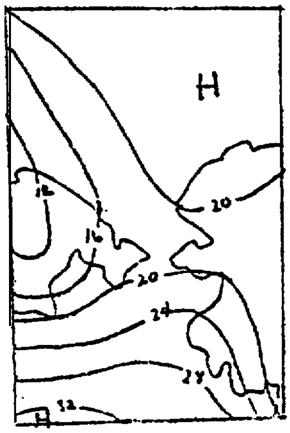


Type 17. 26 December 1968

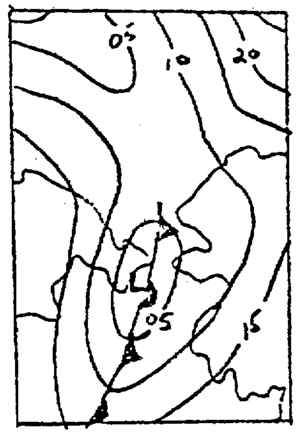


Type 18. 19 July 1963

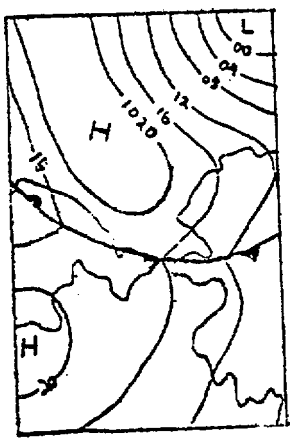
Figure 3c Chukchi Synoptic Types 13 - 18 (isobars in mb, omitting 1000 or 900)



Type 19. 17 October 1964



Type 20. *24* April 1959



Type 21. 7 June 1970

Type *22.* *1* January 1956

Figure 3d Chukchi Synoptic Types 19 - 22 (isobars in mb, omitting 1000 or 900)

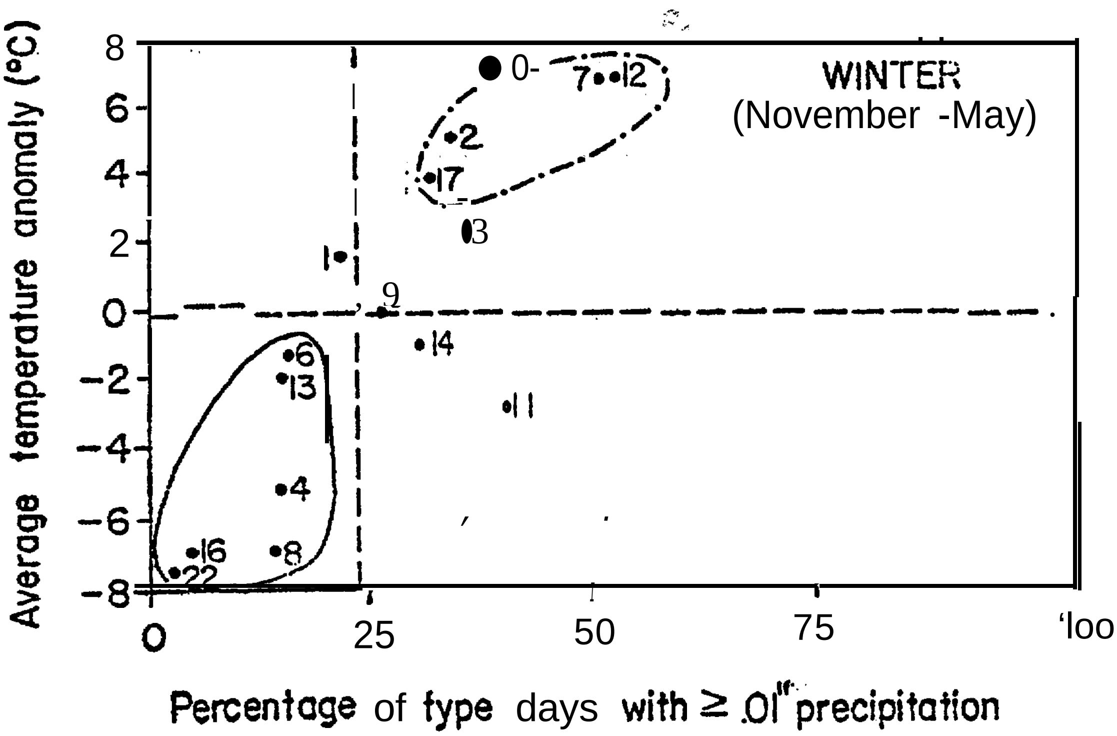


Figure 4 Temperature and precipitation characteristics of winter types. at Kotzebue

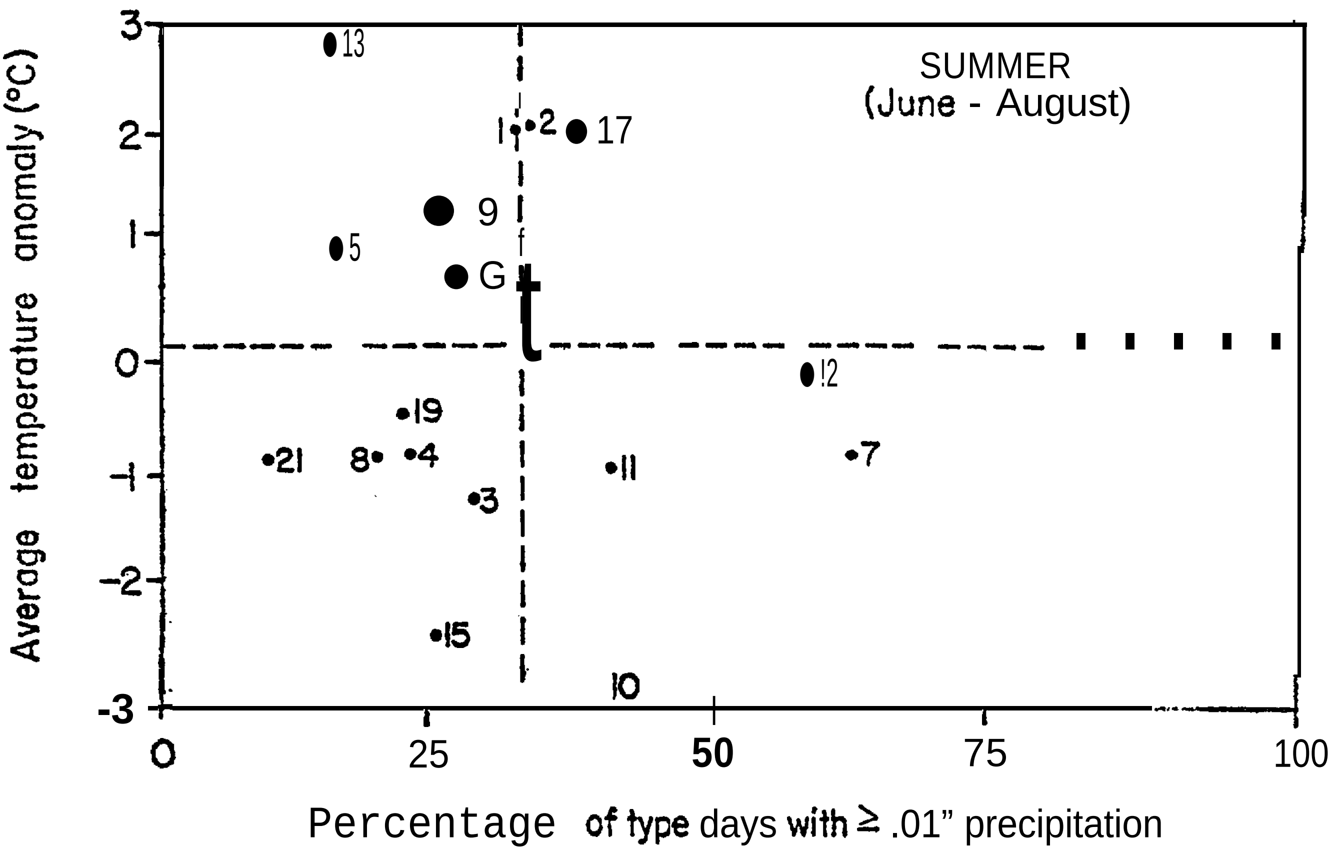


Figure 5 Temperature and precipitation characteristics of summer type at Kotzebue

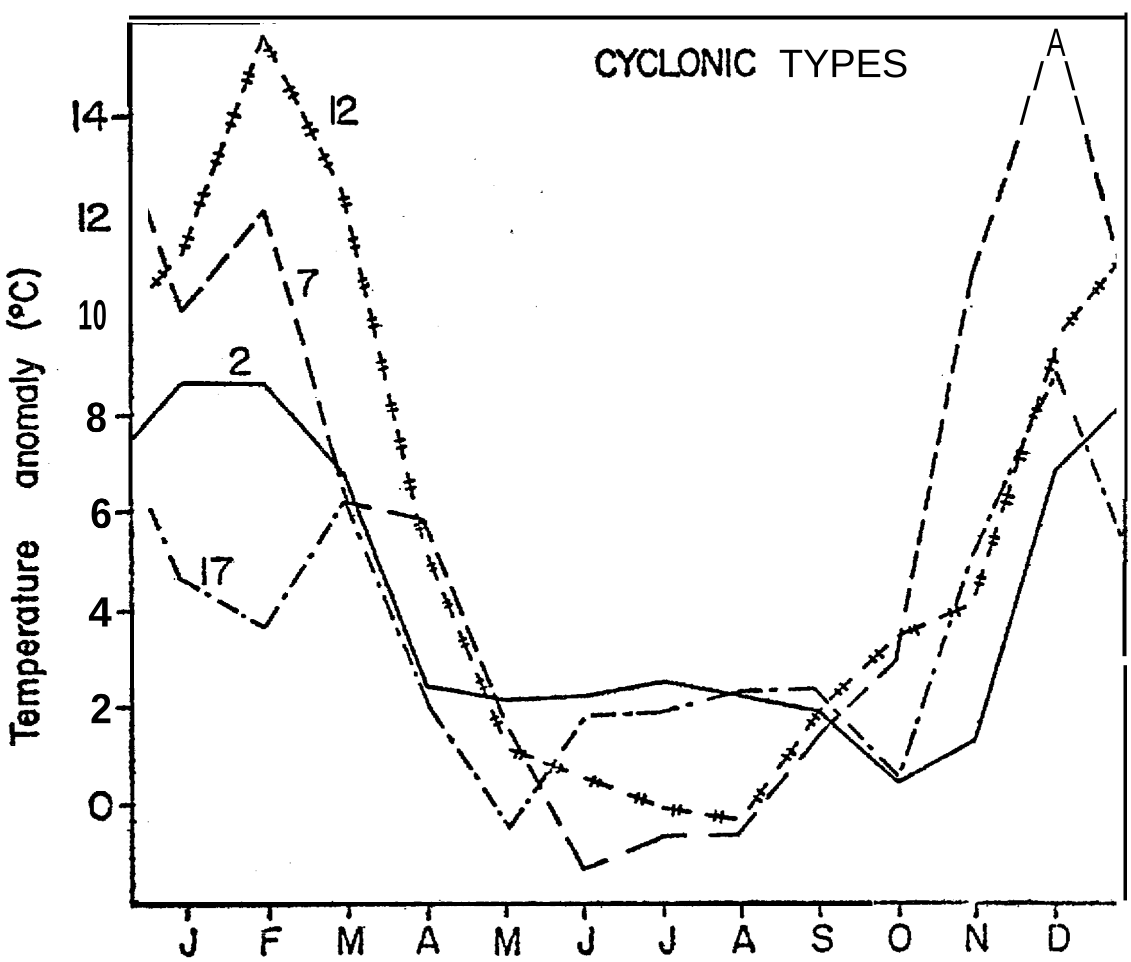


Figure 6 Temperature departure characteristics of the major cyclonic types, at Kotzebue, 1955-1974.

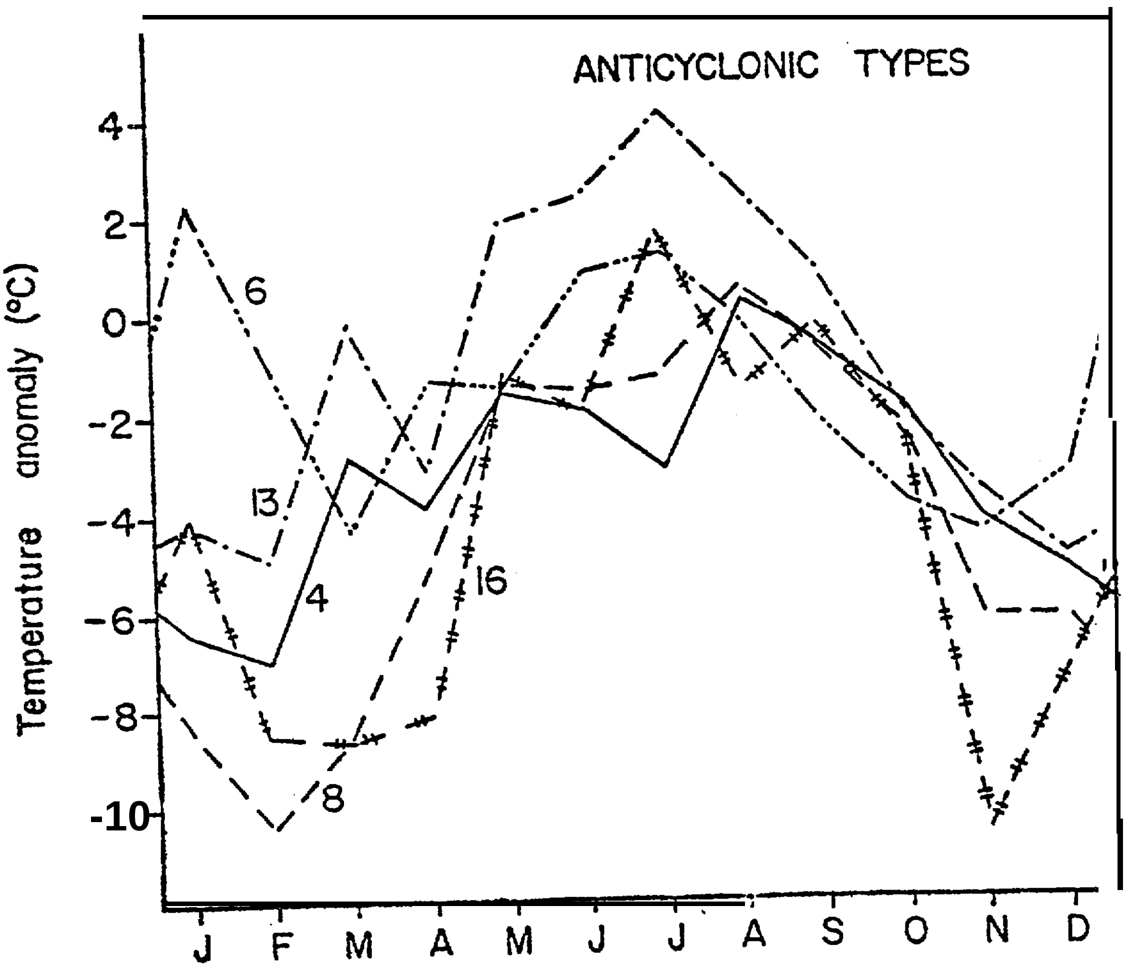


Figure 7 Temperature characteristics of the major anticyclonic types, at Kotzebue, 1955-1974.

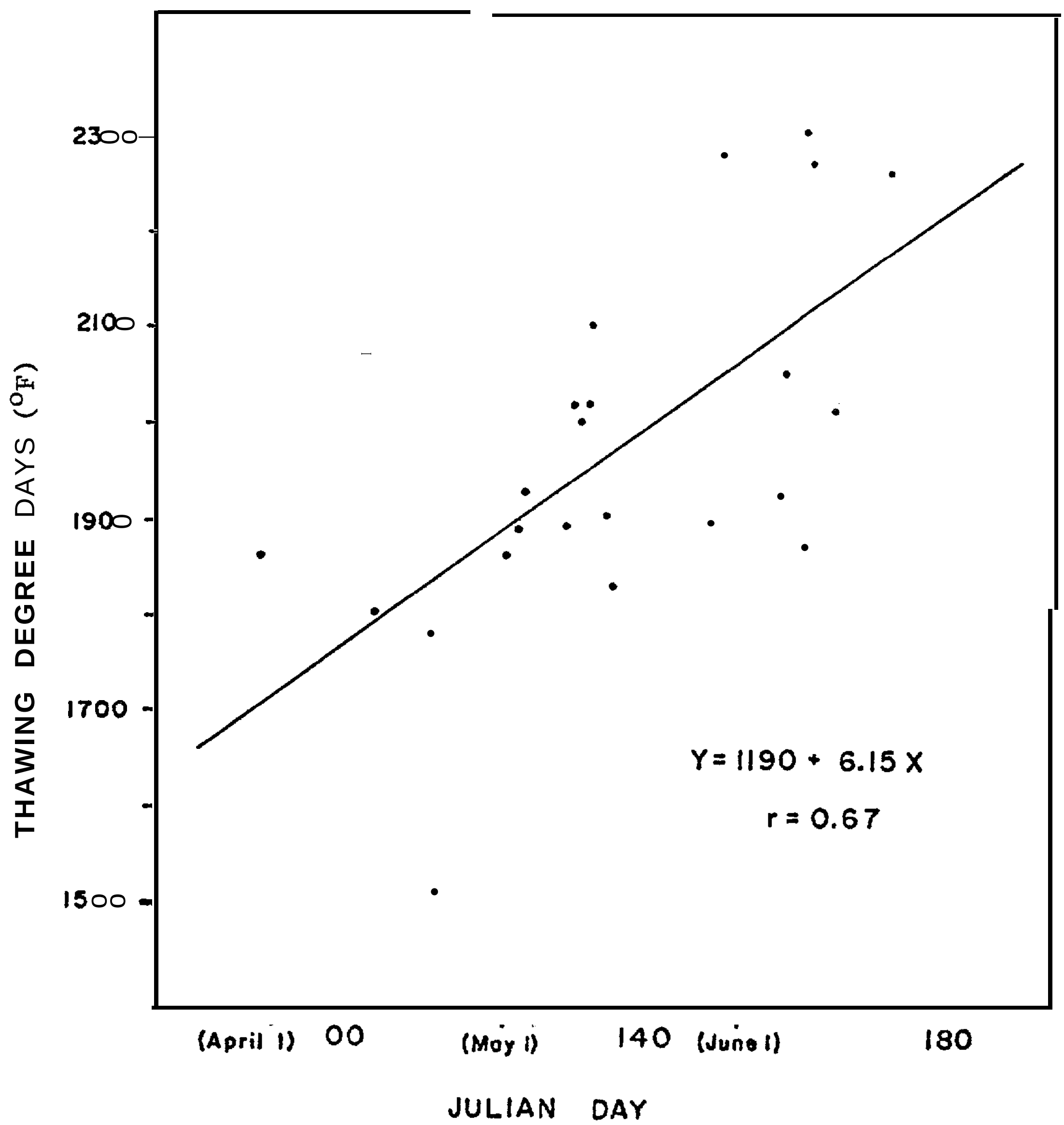


Figure 8 Date of westerly wind onset and accumulated thawing degree days at Kotzebue, 1953-1976 (except 1973). The outlier at approximately 1500 TDD represents the severe summer of 1975.

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	Beaufort Sea		Chukchi Sea	
December 1975	19 pp			
June 1976	6 pp		June 1976	5 pp
September 1976	98 pp		September 1976	27 pp

December 1976	59 pp
June 1977	4 pp
September 1977	194 pp
December 1977	35 pp
June 1978	2 pp
September 1978	13 pp
December 1978	12 pp

Introduction

The ice along the Beaufort and Chukchi Sea coasts of Alaska is the dominant coastal feature for approximately nine months of the year and is receiving intensive study prior to the proposed leasing of continental shelf tracts for petroleum exploration. Drilling operations face major problems due to the severity of the sea ice conditions, and environmental impact assessments therefore require a detailed understanding of the behavior of the ice. In connection with the Offshore Continental Shelf Environmental Assessment Program (OCSEAP) of NOAA-BLM, the seasonal regimes of the near-shore ice have been studied, primarily from remotely sensed data for 1973 to 1976, with special emphasis on the decay season. A major aim of this research is to determine the rate and spatial pattern of the ice decay processes, and to assess the role of climatic factors in determining them. The objective here is to bring together the principal results concerning the seasonal ice regimes of these coastal areas, incorporating the findings of earlier investigations, and to examine the links between the ice cycle and coastal climate. Detailed findings on coastal climatology are presented elsewhere (Barry, 1976; 1977; 1978; Moritz, 1978; Rogers, 1978A; 1978B).

Nearshore ice in the Beaufort Sea has received considerable study in the past few years, although much less attention has been paid to conditions in the Chukchi Sea. Surveys of the nearshore ice environment have been prepared by Kovacs and Mellor (1974) with emphasis on ice surface morphology and sea-floor gouging, and by Reimnitz et al. (1978), who introduced a modified scheme of cross-shelf ice zonation. The latter also gave special attention to the role of shoals and pack ice drift in producing the observed patterns of shear lines and bottom scour. Ice extent and ridging along both the Beaufort and Chukchi coasts have been mapped by Stringer (1974; 1978A) under the OCSEAP, while shore-based radar studies of motion in the nearshore ice have been carried out by Shapiro (1976) at Barrow and by Weeks, et al. (1978) near Prudhoe Bay. Deformation studies from strain gauge networks have been made by Cooper (1975), and investigators of the Beaufort Sea Project (Environment Canada) have conducted remote sensing and other analyses of ice conditions with emphasis on the Canadian sector (Markham, 1975; Marko, 1975; Ramseier, et al., 1975).

Ice Zonation and the Annual Ice Cycle

Fast ice is formally defined as "sea ice which forms and remains fast along the coast, where it is attached to the shore, . . . or between shoals or grounded icebergs" (World Meteorological Organization, 1970). However, the characteristics of ice in the nearshore zone of the Beaufort Sea differ markedly from those in Davis Strait, for example (Jacobs, et al., 1975). The cross-shelf ice zonation on the Beaufort Sea coast has been characterized by Kovacs and Mellor (1974) and Reimnitz, et al. (1978) as comprising zones of fast ice, grounded ridges and seasonal pack ice. The fast ice itself consists of an inner zone of bottom-fast ice, including the ice foot near the beach, and an outer zone of floating fast ice beyond the 2m isobath (approximately). Along much of the coast the seaward limit of the fast ice is fixed at any given time by a zone of grounded pressure and shear ridges, termed "stamukhi" (Transehe, 1928). Free-floating ice may become temporarily attached as a sheet-like extension on the seaward edge of these grounded ridges (cf. Stringer, 1974), which first form in about 8 to 15m deep water, but by late winter may occur beyond the 20m isobath. Since the boundaries of the ice zones and their characteristics change through the year, it has proved difficult to develop a comprehensive, universally-accepted ice nomenclature for the nearshore zones (see Cooper, 1974; Reimnitz, et al., 1978; Stringer, 1978B). Different authors emphasize different aspects of the ice conditions according to the particular objectives of their study (bottom scour, ice dynamics, navigation hazards, and so on) and their various research tools (field measurements, ground, airborne or satellite remotely sensed data), although all of the proposed zonation schemes are most applicable to late winter/spring conditions.

Three criteria which are of general use in distinguishing fast ice from other sea ice are as follows: (i) the ice remains immobile near the shore for a specified time interval; (ii) it extends seaward from the coast as a continuous sheet with no open water; (iii) the ice is grounded, or forms a continuous sheet which is bounded at the seaward edge by grounded ice (ridges, ice island fragments, etc.) . At certain times during winter, ice on the Beaufort coast may be immobile and continuous for a hundred km offshore (within the resolution of LANDSAT imagery ≈100 meters). Such occurrences, involving attached ice and seasonal pack ice, do not meet the third criterion above, although they are an important aspect of the coastal ice environment. A well-defined zone of horizontal ice velocity shear can be used as an indicator of the fast ice edge when the pack is in motion (cf. Stringer, 1974).

The nearshore ice undergoes an annual cycle of formation, growth, extension and decay, finally giving way to open water after breakup. The stages of this cycle can be characterized by a sequence of recurrent ice "events" that can be identified through interpretation of remotely sensed data. These events, which are discussed further below in conjunction with Table 1, are as follows:

(1) new ice formation in the near shore area, (2) freeze-up in bays and lagoons, (3) extension of fast ice seaward of lagoons with modification of the ice sheet by storms and by pack ice stress, (4) over-ice flooding at the river mouths in spring, (5) melt pools forming in situ on the ice surface, (6) openings in previously continuous ice sheets, (7) movements in previously immobile nearshore ice (end of stable fast ice), (8) near-shore area largely free of fast ice. It should be pointed out that "breakup" as defined by Kniskern and Potocsky (1965) for coastal observations, refers to $\leq$ 1/10 ice concentration in the harbor. They note that much higher concentrations may exist outside. Consequently, their tabulations, which are included in other sources (National Ocean Survey, 1977) correspond to our phase 8.

The timing of these recurrent ice events and the duration of the major ice stages have been investigated for both coastal areas. To some extent they are dependent on weather conditions in a given season and the nature of this control has been a major topic of our research. The ice mapping has been based on LANDSAT multi-spectral scanner (MSS) imagery for 1973 to 1977, utilizing mainly bands 4 (wavelengths 0.5-O.6X1OU m) and 7 (O.8-1.1X1OU m), supplemented by some X-band (wavelength x 10-Z m) side-looking airborne radar (SLAR) imagery and color infrared (CIR) photography from aircraft underflights. Low-level aircraft reconnaissance flights, including hand-held photography, were carried out over the ice in early summer 1975, 1976 and 1977. LANDSAT MSS imagery has a spatial resolution capability of about 80 m and provides coverage of a given point on the earth's surface every 18 days, with up to three days consecutive coverage at high latitudes due to image overlap. However, the overcast conditions which prevail during the arctic summer, especially along coasts, render many of these images useless.

In addition to the regular annual cycle of ice formation and decay it is important to consider episodic ice processes which affect the ice canopy through one or more subsequent stages in its development. For example, brief but intense pressure and shear stresses at the fast ice margin can lead to massive ice ridge systems which stabilize the ice to shoreward when they become firmly grounded on the sea floor. Thus it is well to keep in mind that any two ice decay seasons may have similar weather conditions but different breakup rates and patterns, due to differences in the "initial state" of the ice at winter's end.

The Ice Growth Season

Ice conditions along the Alaskan coasts of the Beaufort Sea and the Chukchi Sea differ sufficiently to make it preferable to treat them separately in terms of their seasonal regimes. Points of similarity and contrast are examined later. Approximate dates of the major phases in the fast ice regimes on both coasts are shown in Table 1. However, it must be emphasized that since the satellite observations used in our study cover only five seasons, with frequent data gaps due to cloud cover, the long-term averages may differ from our estimates by about ±7 to 10 days.

The Chukchi Sea Coast

During August surface water temperatures exceed 8°C along the coast south of Cape Lisburne (see Figure 1 for place names), although they drop to less than 4°C north of Wainwright (State of Alaska, 1975, Figure 48; Brewer, et al., 1977). Consequently, new ice begins to form in the nearshore water at the beginning of October to the north, but not until late October at Kotzebue and some time in November nearer the Bering Strait (Table 1). The actual freeze-up date may vary by about ±10 days from these averages, but towards the Bering Strait there is increased variability, both spatially and interannually (cf. Kniskern and Potocsky, 1965).

High winds and waves cause intermittent rafting and destruction of the new ice. Storm surges of up to three meters have been recorded at Point Barrow in October, for example (Schaeffer, 1966). In general, wave heights and surge levels are higher in the Chukchi Sea than in the Beaufort Sea due to the greater fetch over open water that exists on the former coast in summer and autumn. Disruption of the fast ice sheet, with subsequent refreezing, continues into January when the ice has thickened to about one meter or more. According to Peyton and Behlke (1969) floes in the pack ice off the Chukchi coast have a late winter thickness of about 1.2 to 1.5 meters.

The fast ice is extensive in Kotzebue Sound, but in several sections of the coast it forms a narrow belt only a few kilometers wide, due to the relatively steep slope of the bottom near shore. Figure 2 shows these areas off Cape Lisburne, Point Franklin and Point Barrow. Long leads parallel much of the coast in winter and recurrent polynyi (open water areas enclosed by ice) are observed, especially in spring, south of Point Hope, Cape Lisburne, and off Icy Cape. These result from the combined effects of prevailing E-NE winds during winter and spring and occasional south-setting surface currents as inferred by Shapiro and Burns (1975) in March, 1973. Both mechanisms serve to displace the ice away from the coast. The normal water motion is northward (State of Alaska, 1975, Figure 41), except locally south of Point Lay and Point Hope.

The Beaufort Sea Coast

The ice regime on the Beaufort Sea Coast is considerably more complex than on the Chukchi Coast. In part this is due to the important role played by the Arctic pack ice. The pack has a westward drift, averaging 20 km per month in winter and 80 to 100 km per month in summer (Untersteiner and Coon, 1977), through the agencies of the clockwise current gyre in the Beaufort Sea and the prevailing easterly winds over the continental shelf. A second major factor is the relatively gentle slope of the sea floor near the coast. The 20 m isobath is between 25 and 60 km offshore along much of the coast, so that grounded ice can establish itself relatively far from shore compared to the Chukchi Sea. Four discontinuous chains of barrier islands extend along 52 percent of the 800 km Beaufort coast of Alaska with river deltas taking up a further 16 percent (Short, et al., 1974). Landward of the islands, the near shore zone is protected from pack ice incursions, allowing the formation of a continuous, nearly smooth ice sheet. The extensive areas with water depth less than 2 m, especially in Harrison Bay, enable bottom-fast ice to account for as much as 75 percent of the total fast ice cover, according to Reimnitz et al., (1978).

Freezing begins in the lagoons and shallow waters over the inner shelf where salinities are lowest (Reimnitz, et al., 1978). Figure 3 illustrates newly-formed ice between Barter Island and Herschel Island on October 6, 1974. On this LANDSAT scene the light-toned areas near shore correspond to various thicknesses of young ice, which has a high spectral reflectance. The darkest of these near-shore ice areas are either local melting or puddling. Seaward of this fast ice, young ice (dark-grey intone) is forming and being deformed by the pack ice and currents. The roughness of the ice sheet depends on the wave conditions during the early growth phases and on the location of any fragments of multi-year ice, including pressure ridge remnants which survived the melt season (Kovacs 1976), or ice islands. On the open coast and seaward of the barrier islands, however, impingement of the moving pack ice, especially during early winter storms, leads to rafting and hummocking of the growing fast ice sheet. The thin, newly-frozen ice in unprotected areas is free to move away from or along the coast, given only modest wind and water stresses. Figure 3 illustrates the result of this process, showing the jagged fast ice edge after floes have broken off.

There is little information on storm surges in the Beaufort Sea (Aagaard and Contributors, 1978). Reimnitz and Maurer (1978) estimate that surges of three meters or more, such as that of 13 September, 1970 associated with a northwesterly gale, have a recurrence interval of about 100 years during autumn when there is little ice in the nearshore area. However, there are also mid-winter surges, not necessarily linked to local storms, with heights of up to 1.5 meters (Henry and Heaps, 1976) . These may cause flooding of the bottom-fast ice, with subsequent refreezing. Negative surges of 60 to 100 cm (cf. Aagaard and Contributors, 1978) also occur and in winter these can fracture the ice sheet. Moderate pressure due to pack ice impingement is sufficient to disrupt and deform the fast ice until it is at least 0.5 meters thick when it becomes less saline, through brine drainage, and stronger. The shoreward forces of the drifting pack ice are eventually checked by the fast ice sheet itself or by the grounding of pressure ridges on the sea bed (Kovacs and Mellor, 1974). Such grounded ridges often form the seaward boundary of the main fast ice sheet, although attached ice may occur beyond. There are almost no observations covering the period November through February, but it is considered that these ridges tend to form in 8 to 15 meters of water in November and December, and subsequently out to the 20 meter isobath as the ice sheet extends seaward (Fig. 4). Figure 5 is a hand-held, aerial oblique photograph of a typical ice-deformation zone during the early melt season in the fast ice off Barter Island. The pressure and shear ice structures in the figure are roughly 1 to 10 meters high.

From February to early May the ice shoreward of about the 15 m isobath is essentially stable, a factor of major significance for possible oil and gas exploration. Laser measurements of target displacements in the fast ice near Prudhoe Bay show generally small relative motions of about one meter during spring 1976 and 1977, with maximum values of tens of meters (Weeks, et al., 1978). The motion is predominantly outward from the coast and is attributed to thermal expansion, although near the outer margin of fast ice the drifting pack can cause slippage in the shear zone. Deformation of the fast ice diminishes in late winter-early spring as the ice sheet thickens to about two meters and is stabilized by grounding near its edge. However, tidal displacements and diurnal thermal stresses affect the tensile strength of the ice (Nelson, 1974). Tidal cracks are particularly common at the junction of the bottom fast and floating fast ice.

Figures 6 and 7 show a sequence of LANDSAT images which illustrates a striking example of late-winter ice deformation. On Figure 6 (20 April, 1975) dark gray lineations are evident, bounded by the meridians 149°W and 150°W (inside the narrow rectangle). The darkest tones to the north are areas of open water or very thin ice in leads. We interpret the gray lineations as heavy ice-deformation zones which show up because of shadows cast by the piled ice at the low sun elevation angle (30 degrees above the horizon). The ridges clearly were not in this area on March 25 (see LANDSAT MSS scene 1975-21163), so the deformation event must have occurred in late March or early April, much later than is often considered "normal" for such processes. Figure 7 (12 September, 1975) shows much of the 40-km long ridged zone still intact after the melt season. The breakup and removal of surrounding ice indicates that the feature is indeed firmly grounded on the sea floor, without detectable displacement since at least 20 April. The dark gray lineations of 20 April match the brightest tones on the 12 September scene. This reversal of the "spectral signature" is attributed to the drainage of melt water from the elevated ice of the ridges and hummocks. Flatter ice areas with extensive melt puddles and thin, "rotten" ice which has almost melted through appear darker on the late summer imagery, especially in band 7.

The ice feature on these scenes was positioned in waters about 25 meters deep, indicating again the importance of interactions between the shallow inner shelf and the ever-present Arctic pack ice on the Beaufort Coast. Coastal ice conditions were especially severe during the 1975 navigation season (Barnett, 1976) with pack ice over parts of the continental shelf for the entire summer and extremely low coastal temperatures. The ice deformation feature in the figures probably limited the shoreward incursion of pack ice in Harrison Bay during summer, 1975, providing a protected lagoon environment to shoreward. In this way such ice features could be exploited as giant pack ice shields during the summer and fall, if their location and potential stability could be determined in the spring. However, the particular system illustrated in the figures is the largest and longest-lived such structure we observed on LANDSAT imagery for the decay seasons 1973-1976. The possibility of artificially creating ice barriers such as this is under serious consideration as a means of engineering stable operations platforms in the nearshore zone (Clarke, 1976). LANDSAT imagery (not reproduced here) in the same area on 3 November, 1975, shows the grounded ice feature is still in place, with new fast ice extending seaward around it. Again the feature plays the role of a giant ice barrier island far offshore? with a lagoon of sheltered fast ice in Harrison Bay. Our aerial reconnaissance in early summer, 1976 confirmed this sheltering effect, most of the ice in the bay having little or no surface relief (Figure 8). The major ice relief inside the summer, 1976 fast ice edge occurred on fragments of older ice which remained in the nearshore area after the severe summer of 1975 (e.g. Figure 7). These conditions are in marked contrast to those of summer, 1974, when numerous ridge-like deformation systems were located in Harrison Bay using a combination of LANDSAT, CIR and SLAR data. Thus we stress that winter ice events of an episodic character can profoundly influence ice conditions in subsequent seasons.

The Ice Decay Season-General Characteristics

The temporal and spatial characteristics of the ice decay season have been the primary foci of our research. The beginning of the ice decay process is important because it signals the end of the period of stable fast ice, while the final ice clearance marks the start of the possible navigation season. The course of the decay process is determined by the pre-existing ice conditions, especially the occurrence of grounded ridges near the seaward edge of the fast ice, by the "normal" seasonal march of climatic conditions, and by departures from the seasonal norms due to synoptic weather events. Examples of the ways in which these various controls operate are discussed below.

Chukchi Coast

The decay and breakup of ice along the Chukchi coast is different in character from that in the Beaufort Sea due primarily to the orientation of the coastline with respect to the prevailing winds in spring, and to the physiographic character of the coast itself. Barrier islands, which are present along much of the Beaufort Sea coast, are less extensive on the Chukchi Coast of Alaska, although they form numerous almost-closed lagoons along the Seward Peninsula and off Point Lay. 'These account for 32 percent of the 760 km coastline from Cape Prince of Wales to Point Hope and 37 percent of the 580 km coast between Point Hope and Point Barrow. Shallow waters are more restricted off the Chukchi coast where the 20 m isobath is generally 10 to 25 km offshore, which is less than half the average distance off the Beaufort Sea coast.

Along the margin of the shorefast ice (depicted in early summer in Figure 2) there are leads and polynyi. These continually open and refreeze during winter and spring and are the site of the first summer openings in the ice cover. Figure 9 illustrates the extent of open water and thin ice south of Point Hope in 1974 and 1976. The short-term changes indicated on these maps are due to refreezing and to changes in wind direction moving the pack ; winds with a northeasterly component move the ice away from the flaw lead. Even north of Wainwright there may be significant openings paralleling the coast along the fast ice margin by mid-May. Since there are few major rivers along the Chukchi coast, flooding of the nearshore ice is not a dominant component of the decay process, although it is locally important, especially in Kotzebue Sound, due to the Noatak and Kobuk rivers.

Another factor in the Chukchi Sea which differs markedly from conditions on the Beaufort Coast is the role of ocean currents. Handlers (1977) summarizes current measurements and reports that there is generally a northward flow with a velocity of 1.5 m s^{-1} on the east side of Bering Strait, decreasing northward to .2 to .3 m S-l. His analysis of pack ice retreat data for 1972-75 shows that the mean current flows faster than the ice margin retreats northward, thereby extending low salinity water below the ice. The role this advected water layer plays in the heat and mass budget of the ice remains to be determined. The decrease in pack ice concentration which progresses northward in June and July (Brewer, et al. 197"7) facilitates the clearance of fast ice from the coast by winds following its decay in situ during May (Table 1). During the summer months, however, the winds at Kotzebue are predominantly westerly, and this could retard the process. Also, in Kotzebue Sound and in the bay north of Cape Lisburne, local current gyres and the coastal configuration may keep ice trapped against the coast. North of Wainwright, the nearshore ice forms a narrow zone only two to three km wide containing many pack ice remnants. It is subject to considerable pressure ridging. Here the summer rise in temperature serves first to detach fast ice from the beach and later to detach grounded ridges from the sea bed (Shapiro, et al., 1977). During late July 1973, breakup started when winds began to move the floating ice between grounded ridges oriented parallel to the shore. Some ridges may remain in the nearshore zone along the northern section of the Chukchi coast throughout the summer.

Beaufort Sea

The course of a particular ice decay season along the Beaufort Sea Coast is determined by roughly constant factors, including the coastal geography and bathymetry, and the seasonal marches of temperature and incoming solar radiation, and more variable factors such as synoptic changes in regional weather patterns (especially when they involve wind direction anomalies) and prior history of the ice sheet. As noted above, the shallow inner shelf supports an extensive 2m-thick bottom fast ice sheet, especially in Harrison Bay (Reimnitz, et al., 1978, Figure 1). The numerous barrier islands protect much of the flat first-year ice from pack ice impingement and consequent deformation. Figure 4 indicates that coast-to-shear-zone distances off Cross and Narwhal Islands and in Harrison Bay off Atigaru Point are similar from year to year, whereas east of Pt. Barrow and northwest of Prudhoe Bay there is considerable interannual variation. The larger variability west of Cross Island appears to be related to the distribution of shoals and the shear zones which can develop around ice grounded on them. Reimnitz, et al. (1978) report that the location of the fast ice margin is usually coincident with first-year pressure and shear ridge zones which can occur in the depth interval 10 to 30 meters. This pattern is modified by major coastal promontories (e.g. Barter Island, Cross Island, Point Barrow) where seaward fast ice extent is limited, while extensive fast ice exists in the intervening coastal "indentations." A similar pattern is also observed on the Chukchi coast. The fast ice margin is thus significantly affected by shoals, which are themselves altered by the gouging action of deep-draft ice, although the relevant time scale for this process is decades rather than seasons. However, grounded ridges do not necessarily occur in all sections of the coast in every winter season.

The first stage of the Beaufort decay season is major estuarine flooding of the nearshore ice in late May or early June. For example, Carlson (1977) reports that in early June, 1975 the areas of flooded ice on three major river mouths were: Colville 276 km^2, Sagavanirktok 208 km^2, and Kuparuk 101 km^2. In 1974 the flooding of these same estuaries was much less extensive, except in the Sagavanirktok area. On June 6, 1976 (Figure 10) Landsat imagery shows ice flooding extending seaward from several estuaries including the Colville and Sagavanirktok rivers with about 100 km^2 each. Other rivers showing evidence of this phenomenon on Landsat imagery include the Canning, Sadlerochit, Hulahula, Jago and Aichikik. The floodwaters of the Colville River carry sediment onto the ice, reducing the surface albedo and thereby enhancing melt, although the Sagavanirktok River is apparently less sediment-laden (Reimnitz and Bruder, 1972; Carlson, 1977). Due to the flooding, the bottom fast ice begins to float and cracks develop in the ice, especially adjacent to areas of flooding or in situ ablation around the river mouths. The resultant shore polynyi spread laterally and seaward from mid June through early July, while the ice sheet thins and puddles, until wind and water stresses cause the initial openings and displacements in the ice sheet, often towards the shore polynyi. Cracks and openings also occur along the seaward fast ice margin (the flaw lead) due to displacements of the pack ice in the Beaufort Sea gyre.

Figures 11 to 13 comprise a sequence of Landsat MSS scenes in the vicinity of Prudhoe Bay during the decay season, 1974. The sequence illustrates the ice decay processes typical of the Beaufort Coast. Figure 14 is a map of the Prudhoe area containing ice information interpreted from Landsat scenes 1702-21093 and 1703-21151 (25 and 26 June, 1974, respectively). The fast ice sheet can be distinguished from pack ice on 26 June by noting the position of the shoreward-most open water spaces between floes. This line is plotted on Figure 14 as “A.” The sheet of continuous ice need not, of course, be firmly grounded or attached to shore, based solely on this criterion. By overlaying image transparencies for different dates, using the coastline for geographic control, we find ice masses, denoted by “G” on Figure 14, which remained in place while surrounding ice broke up. We take these ice features to be firmly grounded. SLAR imagery* flown 29 April, 1974 indicates that these areas contain ridged and hummocked ice with a very rough appearance. The surface roughness leads to a high X-band radar return, showing up as bright tones on the imagery (Dunbar, 1975; Campbell, et al., 1976). These three ice features are at or very near the 26 June continuous ice edge "A", indicating the role played by grounded ice in determining the fast ice edge. Shore polynyi are evident on the major rivers, and we have outlined these areas on Figure 14. The complex gray tone patterns on the 26 June scene are due to spatial variations in the areal coverage and depth of melt puddles on the ice surface. On this date, the pack ice is compacted along the fast ice margin. Overlay of 25 and 26 June scenes yields the ice displacement vectors plotted on Figure 14. The fast ice is immobile (to within Landsat resolution capability) inside the line "A", while the pack ice far from shore is moving westward at about 10 km per day. The average surface winds at the Oliktok DEW-Line station on 25 June is $6.2 ms^{-1}$ in the direction indicated by "OLI."

Thus the pack ice 20 km or so beyond the fast ice edge drifted as one would expect from "Zubov's rule" for steady, wind-induced ice drift: i.e., at l/30th to l/50th of the wind speed, at an angle about 30° to the right of the wind. More interesting are the vectors in the first 10 km seaward of the line "A". Evidently the pack ice here was nearly motionless, with the pronounced shear zone located some 15 km or more seaward of the fast ice edge. In this instance a buffer zone of immobile pack ice appears to shield the fast ice from shear stresses. It is possible that the coastal promontories or grounded ice areas off Figure 14 to the west stalled the

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* The authors are grateful to J. Wayenberg, U.S. Geologic Survey Ice Dynamics Project, Tacoma, WA, for providing the 1974 SLAR data. The images are from the flights described in Campbell, et al. (1976).

motion of this pack ice, with the momentum of the moving pack dissipated as a normal stress (to the west) against such barriers. In any event, we see that it may be an oversimplification to equate the shear zone with the fast ice edge during the summer.

The 26 June scene illustrates ice conditions just prior to the onset of breakup, with well-developed shore polynyi extending from the major river mouths, a well-defined fast ice sheet including several major grounded ice masses, and a complicated pattern of surficial melt on the fast ice. Figure 12 shows the ice conditions on 14 July, 1974. The shore polynyi on the Colville, Kuparuk and Sagavanirktok rivers have expanded considerably by melting since 26 June. The pack ice is still compact against the near-shore ice. Despite the rapid drift observed on the 25-26 June sequence, several pack ice floes due north of Prudhoe Bay can be positively identified on the scenes of 26 June and 14 July. Their net 18-day displacements are less than 10 km, directed southwest, towards the Colville shore polynya. The fast ice sheet of 26 June has also been displaced by a similar amount between the two westernmost grounded ice features in eastern Harrison Bay. The displacements have large onshore components, the ice shearing away from the immobile grounded masses. The breakup mechanism here appears to be shoreward pressuring of the fast ice by the pack, indicating that offshore wind directions may not be a necessary prerequisite to breakup if the fast ice is sufficiently ablated and weakened. The somewhat more-uniform gray tones on the 14 July scene indicate that most of the fast ice has reached an advanced state of decay via melting at the surface. The 29 April SLAR imagery and 21 June CIR photos show many ice deformation features in the Harrison Bay fast ice. Such features are usually associated with deep-draft keels which, however, must have been floating or grounded less-firmly than the three major ice masses mentioned earlier. As these keels move shoreward under pack ice pressure they can gouge the shallower sea floor, presenting yet another potential hazard for structures or lines along the bottom. Conditions on 14 July are representative of a mid-breakup situation.

By 2 August, 1974 (Figure 13) there is a coast-parallel strip of open water extending 10 to 15 km from shore. The continuous fast ice sheet of 26 June has essentially disintegrated at this time. The three major grounded ice masses which initially stabilized the fast ice edge have decreased in area, but are still located in the same positions as they were on 26 June, indicating once again the potential longevity of ice deformation features in the stamukhi zone.

Breakup in the sector between Point Barrow and Pitt Point lags' areas further east by about one month, probably due to the limited freshwater inflow other than in the lagoons. Ice in Harrison Bay can also be slow to clear as a result of trapping of ice, due to the coastal configuration. Deep surface meltwater ponds often drain through cracks and thawholes in early July, although they ususally become the first sites of complete melt through later in the decay season. Following drainage, the spectral signature of flat first-year ice reverses on the MSS imagery, due to the increase in spectral reflectance of bare ice over puddled ice, especially in band 7. Older floes incorporated into the fast ice, plus the remains of grounded ridges and hummocks, and even ice island fragments, usually beyond the barrier islands, can persist even after the first-year ice has largely melted out in late August. In August 1973, 1974 and 1976 a strip of open water paralleled most of the coast, bordered by loose pack ice, whereas in 1975, fast ice decay was retarded by low summer temperatures in the northwesterly airflow which also held the pack ice close to the coast (Wendler and Jayaweera, 1976; Wohl, 1978). The major shipping delays which accompanied severe ice conditions in August and September, 1975 were primarily caused by the ice accumulation just off Point Barrow, since a channel inside and just seaward of the Barrier Islands was essentially ice free to Prudhoe Bay. We also note that the early summer melt patterns were similar in the Barrow and Prudhoe Bay areas near shore in all four summers 1973-1976.

Climatic Controls

The climatic controls on the fast and pack ice of the Beaufort and Chukchi seas can be differentiated for two regions, one which includes the Beaufort Sea and the northern Chukchi Sea and the other for the southern Chukchi Sea to the Bering Strait. Different climatic controls result from the contrasting orientation of the two Alaskan coasts and the presence of the Brooks Range, although the actual boundary separating these regions is difficult to pinpoint. The Brooks Range, which crosses Alaska between latitudes 67°-69°N, extends westward to Point Hope and it is nearest to the coast in the vicinity of Barter Island. From Icy Cape to Cape Bathurst, N.W.T., the orientation of the coast is roughly east-west and the severity of summertime ice conditions depends primarily upon the predominance of either northerly or southerly winds. South of Icy Cape the coastal orientation is such that easterly and westerly winds affect the nature of ice conditions.

For the Beaufort Sea, southerly and southeasterly surface winds at Barrow are more frequent during light-ice summers while northerly and northeasterly winds are more frequent during heavy-ice summers (Rogers, 1978). The predominance of winds from a particular direction is determined by anomalies in the atmospheric circulation over the Arctic Ocean. Markham (1975) used January, February, and March atmospheric pressure patterns over the Arctic Ocean to estimate the motion of the pack ice and to predict summertime ice conditions in the southeastern Beaufort Sea. His technique, which estimates the volume of ice entering or leaving the Beaufort Sea via the Beaufort Sea gyre, was found to be useful for the southeastern Beaufort Sea in predicting which summers would have extremes of ice conditions.

Between Icy Cape and Point Barrow, north-northeasterly and south-southeasterly surface winds are important in terms of ice movement and breakup. This is particularly true in the fast ice zones of Icy Cape and Peard Bay which have melt and breakup characteristics similar to those occurring along the Beaufort Sea coast. Summertime atmospheric features both north and south of the Brooks Range play an important role in determining the coastal wind regime over the southern Chukchi Sea (Warmerdam, 1978). At Kotzebue, surface winds from 255°-3150 occur on about 41 percent of days during June through September. The Pacific subtropical high pressure intensifies during colder summers at Kotzebue, and the pressure over much of the western Arctic Ocean and northern Alaska is lower than normal. This results in stronger westerly geostrophic flow over the southern Chukchi Sea, which may delay breakup in that area and keep air temperatures below normal. During warmer summers, the south-north pressure gradient is weaker, allowing more occurrences of warm overland flow, but still resulting in mean westerly geostrophic flow. There is a clear correlation (0.67) between date of onset of the westerly regime at Kotzebue and the accumulated thawing degree-days (summers 1953-76, except 1973). The five years of earliest westerly onset were also the summers with the five most severe ice conditions off Barrow. During all summers in recent decades, however, it was warm enough to clear the southern Chukchi Sea coast and Kotzebue Sound of ice.

Northeasterly surface winds normally prevail along both coasts during winter. Along the Beaufort and northern Chukchi coasts this flow is due to a ridge of high pressure over the western Arctic Ocean while over the southern Chukchi Sea it results from the Aleutian low which appears on monthly mean pressure maps. This large-scale flow has considerable influence on the pack ice. Shapiro and Burns (1975) found that during early March 1973 a breakout of ice occurred from the southern Chukchi Sea to the northern Bering Sea through the Bering Strait. This event lowered the ice concentration in the Chukchi Sea by about 10 percent compared with 1974 according to Ahlnäs and Wendler (1977). They showed that during March 1973 the winds were largely from the northeast, which would detach ice from the Alaskan coast, whereas during March 1974 the winds over the Chukchi were from the northwest which would push the ice against the coast. Hibler, et al. (1974) showed that in March 1973 there was also drift of near-shore pack ice from the Beaufort Sea into the Chukchi Sea. These results indicate that strong northeasterly flow around a ridge of high pressure moves the ice from the Beaufort Sea to the Chukchi Sea and can lower the ice concentration near both these Alaskan coasts. During March 1973 this ice movement was facilitated by decreased ice concentration due to preceding ice drift into the Bering Sea.

Large-scale disruptions in the pack ice brought on by atmospheric conditions during winter have important implications for conditions in the fast ice zone. Pack ice movements invariably result in ridging along the edges of the fast ice zone, and they remove ice from the Beaufort Sea gyre (Markham, 1975). Both of these factors may in turn have an influence upon summertime ice conditions and breakup in the fast ice zone. Shapiro (1976) showed how an intense winter storm drove the pack ice into the fast ice zone of the Chukchi Sea coast near Barrow in late December 1973. South-westerly winds of about 90 km hr^{-1} occurred for several hours and drove the pack parallel to the shore at speeds up to 8 km hr^{-1}.

Open water appears in the fast ice zone of the Beaufort Sea after sufficient melting of the ice, puddling, and melting of thaw holes. It is well known from the work of Zubov (1945) and Bilello (1961; 1977) that air temperature expressed as an accumulated freezing or thawing degree-day is the parameter most highly correlated with ice formation, growth, decay, and breakup. A freezing (thawing) degree day is the negative (positive) departure of $1^{\circ}C$ in mean daily temperature from zero. In the Beaufort Sea, fast ice decay and disappearance and pack ice retreat are highly correlated with such temperature indices. Openings and movement in the ice occur with an accumulation of about 55-140 TDDs (°C). With the accumulation of 140-220 TDDs the fast ice is gone and the pack ice starts melting.[1] Southerly winds may clear the nearshore zone by pushing the

[1] Less complete data for northwestern Kotzebue Sound-Kivalina, indicate that the accumulation of about 200 TDDs at Kotzebue approximates to fast ice clearance.

fast ice into the pack ice, which remains continually to the north of the 20 m isobath while the fast ice clears. After 220 TDDs the pack continues melting and retreats northward during southerly winds. The distance of the ice off Barrow on September 15 correlates highly (0.815) with accumulated thawing degree days. It is also affected by surface wind direction and mean surface pressure pattern, although the temperature is correlated with these in turn. Table 2 shows the mean maximum accumulation of summertime TDDs and wintertime freezing degree days. Despite being the northernmost station, and having the coldest winters in terms of accumulated freezing degree days, Sachs Harbor (72°N, 126°W) has warmer summers than those at Barrow and Barter Island. This is due to the high frequency of winds blowing across Banks Island, and to the appearance of open water in late May - early June in the southeastern Beaufort Sea (Markham, 1975). The median date of $\leq 2/10$ ice concentration in the vicinity of Sachs Harbor is about July 2, and it can occur in late May or early June in "good" years. Based on the climatic data and their correlation with the ice clearance, it is believed to have been sufficiently warm to have cleared the fast ice zone along the Beaufort Sea during all summers since 1921, when continuous meteorological data became available at Barrow (Rogers, 1978B).

Implications for Offshore Development

Until recently, marine transportation has been the primary activity in the Beaufort and Chukchi Seas for which ice hazards were a major concern. If petroleum exploration and development begin along the Alaskan continental shelf, activities related to exploratory drilling, such as determining the type and location of drilling platforms, and others related to development, production, and transport of oil from offshore to pumping stations will also face problems with ice conditions and movement. Over-ice transport of equipment and supplies will be feasible and will depend upon ice conditions.

The degree of hazard posed by ice conditions to each of these activities depends upon where and how far from shore they are undertaken, i.e. , on the type of sea ice (Weeks, 1978). The development of petroleum faces the least risk shoreward of the barrier islands and in the bottom-fast ice zone where wintertime ice motion is small (meters), or non-existent. Large (on the order of kilometers), and therefore hazardous, ice motions in this region occur primarily in autumn before ice becomes fast to the sea floor, and in late spring. However, recent studies by Taylor (1977), and Kovacs and Sodhi (1978) demonstrate that shore ice pile-up and ride-up is a common event on most arctic beaches. Ice ride-up may extend 50-150 m inland with both thick and thin sea ice. Such events appear to be most common in spring and early winter and may last only 15-30 minutes.

Increasingly greater risk to petroleum development would occur for activities undertaken in the floating fast ice zone and seaward. Large variations in ice conditions from year to year characterize the floating fast ice zone. These variations are dependent upon the forces and movements which can occur in this region during autumn before the fast ice is strong (thick) enough to resist deformation. There is evidence that colder winters are associated with less ice motion in this zone, although movement is always possible. The formation of small leads due to ice motion is hazardous to ice surface transportation particularly if the lead rapidly refreezes and becomes snow covered. Hazards in the floating fast ice zone are considerably less shoreward of the 10-15 m isobath. Seaward of this there is greater potential of ice deformation and formation of grounded ridges. These are now discussed in more detail.

Ice deformation features. Ridges and hummocks show more-or-less preferred locations from year to year, probably in relation to the location of shoals (see Reimnitz, et al., 1978; Stringer, 1978A). Examples are: offshore and west of Barter Island, in a line from Narwhal Island to a point approximately 80 km due north of Atigaru Point in Harrison Bay, and approximately along the 20m isobath arcing aroun Pt. Barrow in the Chukchi Sea and Beaufort Sea. These areas are the scene of enormous shear and pressure forces, most of which seem to occur during the dark period November through February.

Since the edge of contiguous fast ice appears to be displaced progr s-sively seaward through the winter months, each successive winter ice edge can be a site for ice deformation. Thus, large grounded ice masses may occur well inside the 20m isobath. In general, however, the areal extent and intensity of ice deformation seems to be greatest near the late-winter fast ice edge in the stamukhi zone. This may be a consequence of the involvement of more massive polar floes and thicker first-year ice in ridge formation late in the season. Our case-study illustrates the anomalously large and well-grounded field of shear ridges that may form in this manner.

Grounded ice. This type of ice is very discontinuous along the coast. During the decay season, therefore, under-ice oil spills occurring within the fast ice zone would not necessarily be contained within a band of grounded ice parallel to the coast. Nevertheless, the elongate ridges which parallel extensive segments of the Beaufort Sea coast in late winter have keels extending well below the level ice, even though they may be floating or only weakly grounded. These ridges might be effective in temporarily containing most of an under-ice oil spill during February through May. Such trapping capability would rapidly diminish after late June as the fast ice begins to disintegrate leaving only well-grounded ridges _in situ_. This decay date also marks the end of the period when trapping could occur in the irregular bottom topography of the floating fast ice.

Our mapping has shown that well-grounded, deformed ice masses are occasionally found in waters ≤10m deep. Structures and lines on the near-shore bottom must be able to withstand the forces generated by such features and associated bottom gouging and scour, even though the frequency and intensity of such events are much less than in the _stamukhi_ zone.

During virtually all summers, the fast ice zone clears of ice (Rogers, 1978) with pack ice retreat occurring during summers with more frequent southerly winds. While this is encouraging for setting up structures in the open water of the bottom fast ice and floating fast ice zones, there is always the danger of pack ice incursions due to wind shifts over the course of the summer. This problem may be alleviated by ice reconnaissance and improved ice forecasting, but structures or shipping operations must take account of this hazard.

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Summary

The fast ice regimes of the Beaufort-Chukchi Sea coasts are described, based on LANDSAT imagery for 1973-76, in order to outline the timing of the seasonal states. The spring location of the outer fast ice margin is strongly influenced by the occurrence of grounded ridges along much of the Beaufort Sea coast. However, for about 2° longitude eastward from Point Barrow, and also north of Cape Lisburne and off Kotzebue, the limit is much more variable from year-to-year, apparently in response to the particular patterns of current gyres, pack ice drift, and shear. The significance of winter ridging events for the summer breakup process is illustrated by case studies. A flaw lead and polynyi are major features of the Chukchi coast. The decay process is closely related to thawing degree day accumulations; approximately 140-220 TDDs (°C) are required to remove the fast ice and 220-300 for open water to extend up to 80 km off Pt. Barrow on 15 September. Surface winds are more frequent from 135°-1950 during light-ice summers on the Beaufort coast, and from 345°-0450 during severe ice summers, reflecting the airflow direction-temperature association. Based on the climatic data at Barrow and their correlation with ice clearance, the fast ice in the nearshore zone of the Beaufort Sea coast should have cleared in all summers since 1921. Some implications of the characteristics of the fast ice zone in the Beaufort Sea for potential offshore developments are discussed.

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TABLE 1. Average seasonal regimes in Alaskan shorefast ice[1].

Ice Phase	Central Beaufort Sea Coast	Central Chukchi Sea Coast
New ice forms	3 October	10 October
First continuous fast ice	Mid October	Early November
Extension/modification of fast ice	Nov. - Jan./Feb.	Nov./Dee. - Jan./Feb.
Stable ice sheet inside 15 m isobath	Jan./Feb. - Apr./May	Feb. - Apr./May[2]
River flooding fast ice	25 May	1 May
First melt pools	10 June	10 May
First openings and movement	30 June	10 June
Nearshore area largely free of fast ice	1 August	5 July

[1] These dates are based on available LANDSAT imagery for 1973-77. An identifiable event may occur anywhere between the dates of available clear frames which bracket the latest date of recognized non-occurrence and the earliest date of its identified occurrence; the average of these dates is used here.

[2] Locally, the ice may not achieve any prolonged stability.

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FIGURE CAPTIONS

1. Location map of the Beaufort-Chukchi Sea coasts.
2. Spring-early summer limits of the fast ice zone on the Chukchi coast, 1973-76.
3. LANDSAT scene showing nearshore ice conditions on 6 October, 1974, between Barter Island and Herschel Island.
4. Spring-early summer limits of the fast ice zone on the Beaufort coast, 1973-76.
5. Low-level aerial oblique photograph of the ice-deformation zone off Barter Island, June 1976.
6. LANDSAT scene showing a large ridge field in outer Harrison Bay, 20 April, 1975.
7. LANDSAT scene showing the same area as Fig. 6 on 12 September, 1975.
8. Low-level aerial view of flat ice in Harrison Bay, June, 1976.
9. The extent of polynyi off Point Hope in spring-early summer, (a) 1974, and (b) 1976, mapped from LANDSAT imagery.
10. LANDSAT scene showing rivers flooding over ice in the vicinity of Prudhoe Bay, 6 June, 1976.
11. LANDSAT scene showing pre-breakup conditions in the vicinity of Prudhoe Bay, 26 June, 1974. Polynyi are evident off the major river mouths.
12. LANDSAT scene showing mid-season nearshore ice breakup in the vicinity of Prudhoe Bay, 14 July, 1974.
13. LANDSAT scene showing post-breakup conditions in the vicinity of Prudhoe Bay, 2 August, 1974. A coastal strip of open water extends 10-15 km from shore. Three major grounded ice masses are located in the same positions as on 26 June.
14. Mapped interpretation of ice conditions in the vicinity of Prudhoe Bay on 25-26 June, 1974. The fast ice/pack ice boundary is marked 'A'. Grounded ice masses which persisted into August are marked 'G'. Ice displacement vectors have been determined between 25 and 26 June. Average surface wind direction at Oliktok on 25 June is denoted 'OLI'.

TABLE 2. Average cumulative thawing and freezing degree-days (°C).

	Period	Thawing degree-days Mean	Thawing degree-days Standard deviation	Freezing degree-days Mean
Kotzebue	1943-76	1081	113	3414
Barrow	1921-75	296	101	4836
Barter Is.	1948-75	324	98	4877
Sachs Harbour	1956-75	364*		5382*

*based on mean monthly temperatures.

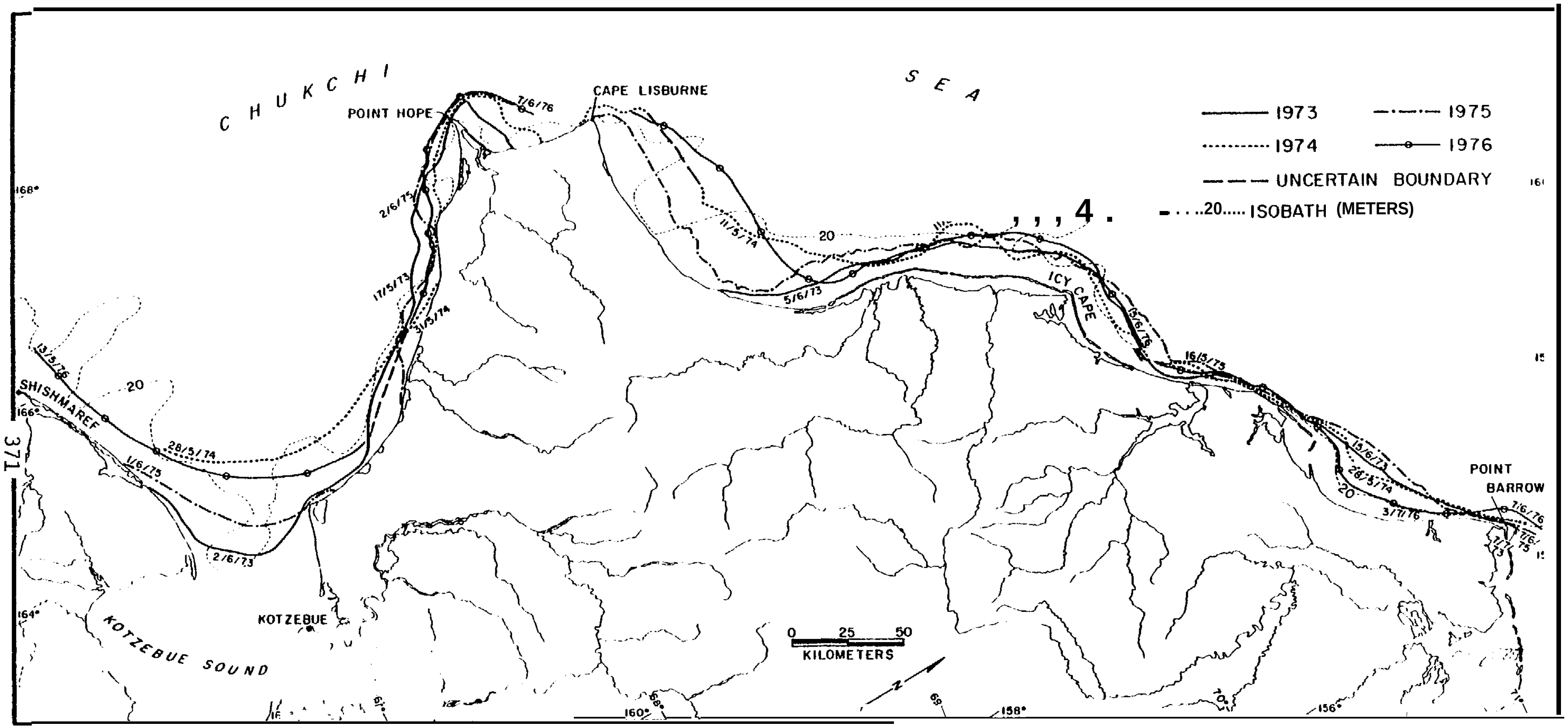

Fig. 2. Spring-early summer limits of the fast ice zone on the Chukchi coast, 1973-76.

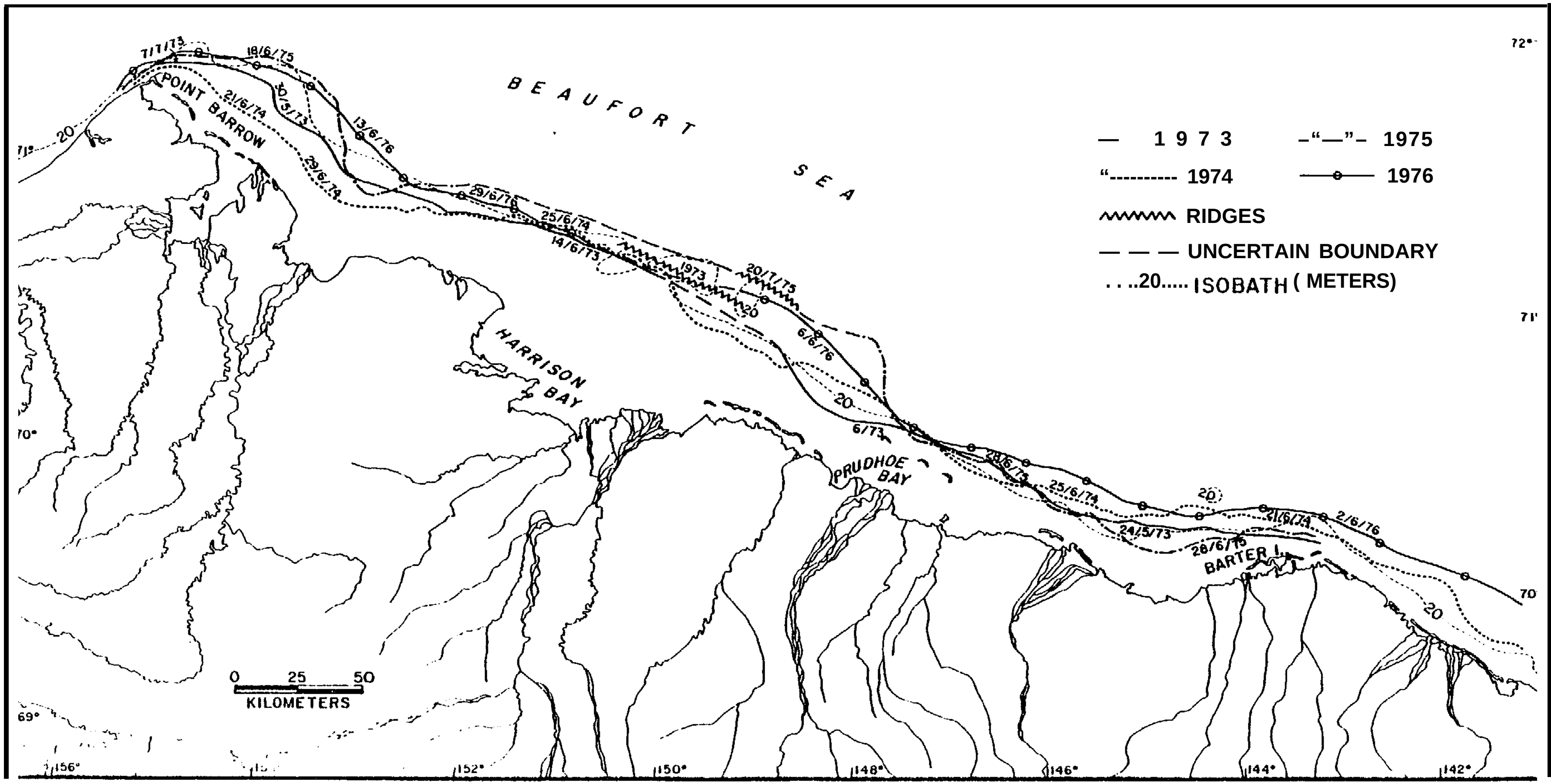

Fig. 4. Spring-early summer limits of the fast ice zone on the Beaufort coast, 1973–76.

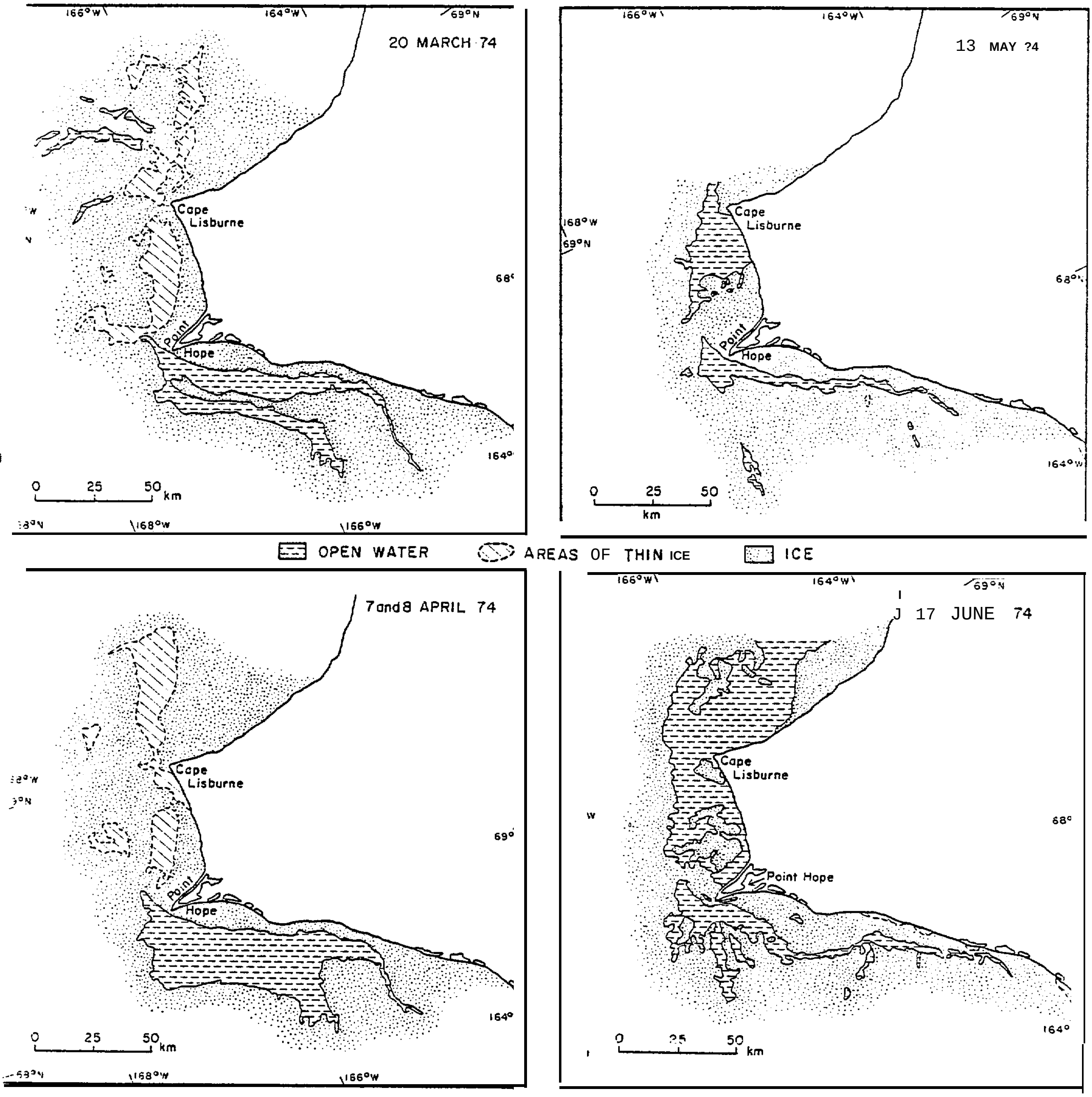

Fig. 9a. The extent of polynyi off Point Hope in spring-early summer, 1974, mapped from LANDSAT imagery.

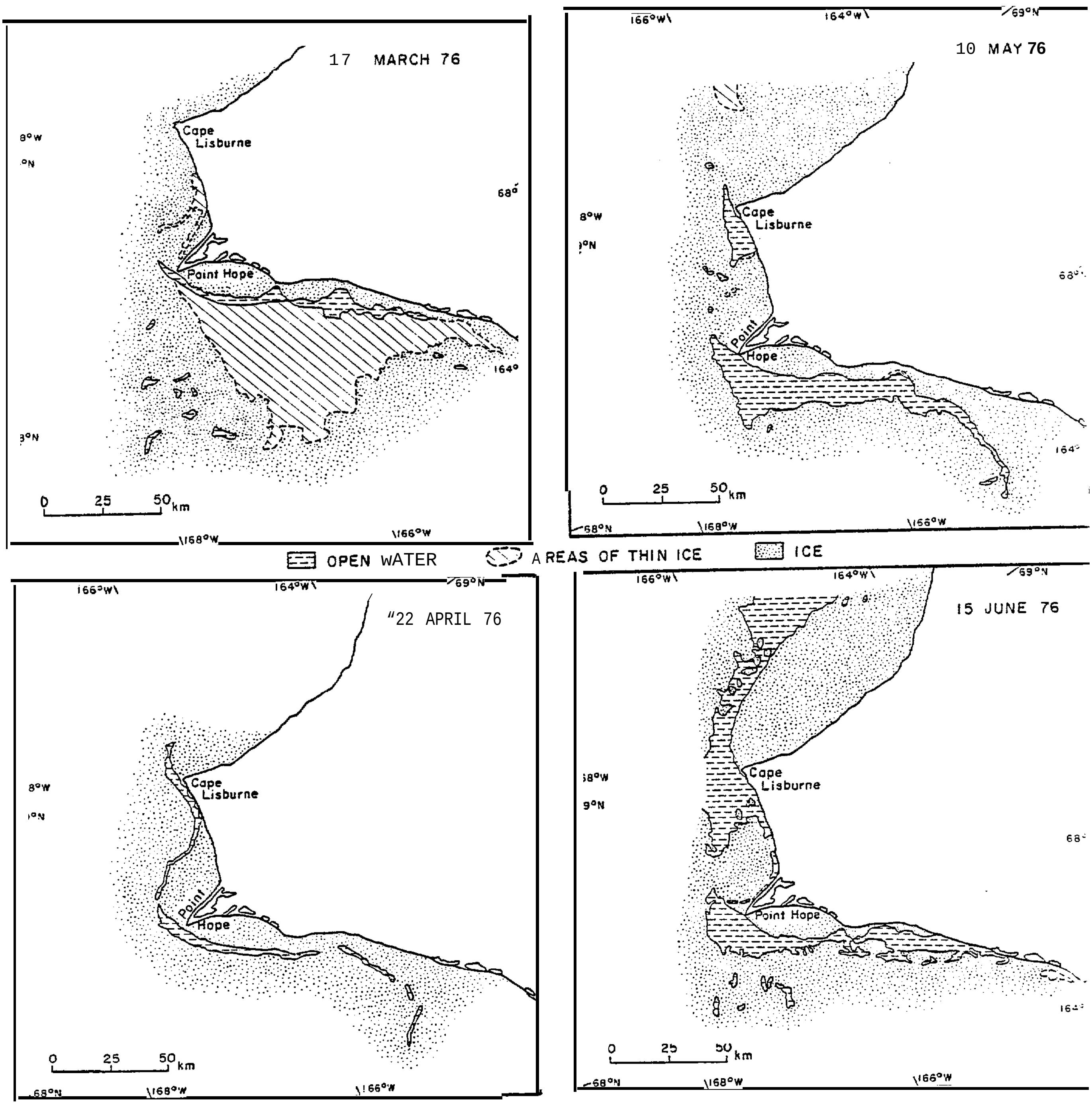

Fig. 9B. The extent of polynyi off Point Hope in spring-early summer, 1976, mapped from LANDSAT imagery.

The following was submitted as Appendix 2:

Rogers, Jeffery C. (1978). “Meteorological Factors Affecting Inter-annual Variability of Summertime Ice Extent in the Beaufort Sea,” Monthly Weather Review, Vol. 106, No. 6, pp. 890-897.

The following was submitted as Appendix 3:

Rogers, Jeffrey C. (1977). “A Meteorological Basis for Long-Range Forecasting of Summer and Early Autumn Sea Ice Conditions in the Beaufort Sea,” POAC 77, Vol. 2, pp. 952-962.

Research Unit 257

The following were submitted as the final report for this research unit:

Stringer, William J. (1978) Morphology of Beaufort, Chukchi and Bering Seas Nearshore Ice Conditions by means of Satellite and Aerial Remote Sensing. Geophysical Institute, University of Alaska, Fairbanks, AK 99701.

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